NRCS National Engineering Handbook

Part 623
IRRIGATION

Chapter 4
Surface Irrigation

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GLOSSARY

ac-ft A common English unit for water volume called an "acre-foot". It is the volume of water required to cover an acre with water one foot deep. One ac-ft equals 325,851 gallons or 1,233 cubic meters.

advance phase The period of time between the introduction of water to surface irrigated field and the time when the flow reaches the end of the field.

advance time (t_L) The elapsed time between the initiation of irrigation and the completion of the **advance phase**. Usual units are minutes or hours.

application efficiency (E_a) See **irrigation efficiency**.

available water (AW) Soil moisture stored in the plant **root zone** between the limits of **field capacity (FC)** and the **permanent wilting point (PWP)**. Sometimes referred to as **allowable soil moisture depletion** or **allowable soil water depletion**. Usual units are inches of water per inch of soil depth.

basic intake rate (f_o) The final or steady state infiltration rate of a ponded soil surface. Usual units are cubic feet per foot of length per minute for furrows and feet per minute for borders and basins.

basin irrigation Irrigation by flooding level fields. The perimeter of basins is usually fully contained by surrounding dikes.

block-end The practice of using dikes at the downstream end of the surface irrigated field to prevent or control **runoff** (**tailwater**).

border irrigation A surface irrigation configuration in which irrigation is applied to rectangular strips of the field. Borders typically have a slope in the direction of irrigation but not laterally.

bulk density (γ_b) Mass of dry soil per unit volume. Typical values in irrigated soils range from about 65 pounds per cubic foot (lbs/ft^3) (1.05 g/cm^3) for a clay soil to as much as 100 lbs/ft^3 (1.6 g/cm^3) for sandy soils.

cablegation An automated surface irrigation system employing a continuously moving plug in sloping gated pipe. Outlet flows are highest near the plug and diminish away from it thereby creating a cutback regime.

cfs Abbreviation for "cubic feet per second", a common English unit of discharge which is a rate of the flow or discharge equal to 448.8 gallons of water flowing each minute, **gpm,** or 28.32 liters per second (**lps**).

chemigation The process of applying chemicals to an irrigated field through the irrigation stream. Chemigation is also referred to as **fertigation** when used to define through-system fertilizer applications.

consumptive use The water extracted by plants from the soil during their growth process or evaporated from the cropped surface (plant and soil). Usual units are inches.

contour irrigation The practice of arranging ***furrows***, ***borders***, or ***basins*** along the natural contours of a field.

conveyance efficiency See ***irrigation efficiency***

conveyance loss Water lost from the conveyance system due to evaporation, seepage from the conveyance (ditch, pipe, canal, etc.), leakage through control and turnout structures or valves, or is unaccounted for due to measurement errors.

cropping pattern The term cropping pattern has two connotations. The first is the seasonal sequence of crops grown on a single field. The second is a more general term describing the distribution of cropped acreages in an area in any one year.

crop root zone The soil depth from which crop extracts the water needed for its growth. This depth depends on the crop variety, growth stage, and soil. Usual units are inches or feet.

cumulative intake (z, Z) The depth (z) or volume per unit length (Z) of water infiltrating a field during a specified period, usually the time between the initiation of irrigation and the end of the recession phase. Usual units are feet or inches for z and cubic feet per foot of length for furrows.

cutback irrigation The practice of using a high ***unit discharge*** during the ***advance phase*** and a reduced one during the ***wetting or ponding phase*** to control runoff.

cutoff time (t_{co}) Cumulative time since the initiation of irrigation until the inflow is terminated. Also referred to as ***set time.*** Usual units are minutes or hours.

cycle time Length of water application periods, typically used with surge irrigation. Usual units are minutes.

deep percolation (DP) The depth or volume of water percolating below the ***root zone***. The depth or volume of deep percolation divided by the average depth or volume of water applied to a field is the ***deep percolation ratio (DPR).***

deficit irrigation The practice of deliberately under-irrigating a field in order to conserve water or provide a capacity to store expected precipitation.

depletion time (t_d) The elapsed time between the initiation of irrigation and the recession of water following cutoff at the field inlet. Usual units are minutes.

distribution system The network of ditches or pipes, and their appurtenances, which convey and distribute water to the fields.

ditch Constructed open channel for conducting water to fields.

ditch gate Small controlled opening or portal in a ditch used to divert water directly to furrows, borders, or basins.

distribution uniformity (DU) See ***uniformity.***

effective precipitation Portion of total precipitation which becomes available for plant growth.

evapotranspiration See ***consumptive use.***

fertigation	See *chemigation.*
field bay	A narrow strip at the head of an irrigated field which is constructed slightly below field elevation used to redistribute water flowing from a pipe or ditch before flowing over the field.
field capacity (W_{fc})	The dry weight soil moisture fraction in the root zone when vertical drainage has effectively ceased following irrigation or heavy rainfall. Generally, field capacity is assumed to occur at a negative one-third atmosphere or one bar of soil moisture tension.
field length	The dimension of the irrigated field in the direction of water flow. Usual units are feet.
flow rate (q, Q)	The volume of water passing a point per unit time per unit width (*q*) or per furrow (*Q*). Another term for flow rate is *discharge*. See also *unit discharge*. In surface irrigation flow rate is typically expressed in units of *cfs* or *gpm*.
flood irrigation	An alternative expression for surface irrigation.
furrow irrigation	The practice of surface irrigation using small individually regulated field channels called furrows, creases, corrugations, or rills.
gated pipe	Portable pipe with small individually regulated gates installed along one side for distributing irrigation water onto a field.
gpm	Acronym for gallons per minute. See also *cfs, unit discharge*.
head ditch	A small channel along one part of a field that is used for distributing water in surface irrigation.
infiltration	The process of water movement into and through soil.
infiltration rate (I)	The time-dependent rate of water movement into an irrigated soil. Usual units are inches or feet per minute or hour.
infiltrometer	A device, instrument, or system to measure infiltration rates.
intake family	Grouping of intake characteristics into families based on averge 6-hour intake rates.
intake rate	A term often used interchangeably with *infiltration rate* but in technical terms is the process of infiltration when the surface geometry is considered such as in furrow irrigation.
intake reference flow (Q_{infilt})	The discharge at which intake is measured or evaluated in a surface irrigation system. Usual units are *cfs* or *gpm*.
irrigation efficiency	In general terms the efficiency or performance of an irrigation system is measured or expressed as the amount of water used beneficially by the crops divided by the total amount of water made available to the crops. In order to provide more specific assistance in evaluating irrigation performance of surface irrigation systems at the field level, the following terms have been defined:

application efficiency (E_a)   The ratio of the average depth or volume of the irrigation water stored in the root zone to the average depth or volume of irrigation water applied to the field. Inefficiencies are caused by *deep percolation* and *tailwater* losses.

conveyance efficiency (C_e)   Ratio of the water delivered, to the total water diverted or pumped into an open channel or pipeline at the upstream end. Inefficiencies are caused by leakage, spillage, seepage, operational losses and unaccountable water due to poor measurement.

irrigation efficiency (I_e)   At the field level, irrigation efficiency is the ratio of the average depth or volume of irrigation water stored in the root zone plus the depth or volume of deep percolation that is needed for leaching to the average depth or volume of irrigation water applied. Inefficiencies are caused by *tailwater* and *deep percolation* losses above the *leaching requirement*.

storage or requirement efficiency (E_r)   Ratio of the amount of water stored in the root zone during irrigation to the amount of water needed to fill the root zone to field capacity. Inefficiencies are caused by under-irrigating part of the field.

irrigation interval   The interval between irrigation events. Usual units are days.

irrigation requirement   Quantity of water, exclusive of effective precipitation, that is required for crop demands including evapotranspiration, leaching, as well as special needs such as seed bed preparation, germination, cooling or frosts protection. Where there is an upward flow from a shallow groundwater, it should reduce the amount of water required from the irrigation system. The *irrigation requirement* is often called the *"net" irrigation requirement*. Recognizing that no irrigation system can exactly supply the irrigation requirement due to inefficiencies, a *"gross" irrigation requirement* is often estimated by dividing the irrigation requirement by an irrigation efficiency term. Usual units are inches.

irrigation set   A subdivision of the field that is individually irrigated. Sets are generally required whenever the supply flow is too small to irrigate the entire field at once.

land leveling   A general reference to the process of shaping the land surface for better movement of water. A more correct term is *land grading*. When land grading is undertaken to make the field surface level, the term *land leveling* can be used as a specific reference. Related terms are land forming, land smoothing, and land shaping.

leaching   The process of transporting soluble materials from the root zone in the deep percolation. The most common of these materials are salts, nutrients, pesticides, herbicides and related contaminants.

leaching fraction (LF)   Ratio of the depth of deep percolation required to maintain a salt balance in the root zone to the depth of infiltration. Also referred to as the *leaching requirement.*

MAD (z_{req}, Z_{req})   An abbreviation for **management allowable depletion** or **maximum allowable deficiency**. **MAD** is the soil moisture at which irrigations should be scheduled. In the evaluation or design of surface irrigation systems, MAD is referenced as a required depth per unit length, z_{req}, or a volume per unit length per unit width or furrow spacing, Z_{req}.

opportunity time (τ_{req})   The cumulative time between **recession** and **advance** at a specific point on the surface irrigated field. Usual units are minutes or hours.

permanent wilting point (W_{pw})   Moisture content, on a dry weight basis, at which plants can no longer obtain sufficient moisture from the soil to satisfy water requirements and will not fully recover when water is added to the crop root zone. Classically, this occurs at about -15 atmospheres or15 bars of soil moisture tension.

porosity (φ)   The ratio of the volume of pores in a soil volume to the total volume of the sample.

pump-back system   See **tailwater reuse system.**

recession phase   A term referring to the drainage of water from the field surface following the termination of inflow.

recession time (t_r)   The interval between the initiation of irrigation and completion of the **recession phase**. Usual units are minutes or hours.

resistance coefficient (n)   A parameter in the Manning Equation that provides an expression of hydraulic resistance at the boundary of the flow.

return flow   Deep percolation, tailwater, conveyance seepage, and spills from an irrigation system which flow into local streams, rivers, lakes, or reservoirs.

run length (R_L)   Distance water must flow over the surface of a field to complete the **advance phase.** The **field length** is the longest run length. Usual units are feet.

runoff   A general term describing the water from precipitation, snow melt, or irrigation that flows over and from the soil surface. In surface irrigation, runoff is used interchangeably with **tailwater.**

run time (R_T)   See **cutoff time.**

saturation (S)   The ratio of the volume of water to the volume of pore space in a soil.

siphon tube   Relatively short, light-weight, curved tube used to divert water over ditch banks.

slide gate   A regulated ditch or canal offtake used to divert water to irrigated borders and basins. See also **ditch gate**.

soil dry weight   The weight of a soil sample after being dried in an oven at 95-105 $^{\circ}$C for 12-24 hours. Usual units are grams since as metric units are typically used for these measurements.

soil moisture content (θ)   The ratio of the volume of water in a soil to the total volume of the soil.

soil moisture depletion (SMD)   The depth or volume of water that has been depleted from the ***available water*** in a soil. This can also be viewed as the amount of water required to return the soil moisture to ***field capacity.***

specific gravity (γ_s)   The ratio of the unit weight of soil particles to the unit weight of water at 20 °C.

spile   A small pipe or hose inserted through ditch banks to transfer water from an irrigation ditch to a field.

subbing   The horizontal movement of water from a furrow into the row bed.

surface irrigation   A broad class of irrigation systems where water is distributed over the field surface by gravity flow. See ***border, basin*** and ***furrow irrigation***.

surge irrigation   Surface irrigation by short pulses or surges of the inflow stream during the ***advance phase*** and then by high frequency pulses or surges during the ***wetting or ponding phase***.

tailwater   See ***runoff.***

tailwater reuse system   An appurtenance for surface irrigation systems where there is tailwater runoff. The tailwater is first captured in a small reservoir and then diverted or pumped back to the irrigation system, i.e., either to the same field or to anther in proximity.

uniformity   Irrigation uniformity is a qualitative measure of how evenly water is applied by the surface irrigation system.

   distribution uniformity (DU) In surface irrigation, the distribution uniformity is the ratio of the depth or volume infiltrated in the least irrigated quarter (sometimes called the low quarter) of the field to the average depth or volume infiltrated in the entire field.

unit discharge   The discharge or flow rate of water applied to an irrigated field per unit width or per furrow. Typical units are ***cfs*** and ***gpm***.

wetted perimeter   Length of the wetted contact per unit width between irrigation water and the furrow, border, or basin surface, measured at right angles to the direction of flow. Usual units are inches or feet.

wetting or ponding phase   The period of time in an irrigation event between the completion of ***advance phase*** and the ***cutoff time***.

wild flooding   Surface irrigation system where water is applied to the soil surface without flow controls and without management of flowrate and cutoff time.

I   *The Practice of Surface Irrigation*

I.1   INTRODUCTION

Surface irrigation is the oldest and most common method of applying water to croplands. Also referred to as "flood irrigation", the essential feature of this irrigation system is that water is applied at a specific location and allowed to flow freely over the field surface and thereby apply and distribute the necessary water to refill the crop root zone. This can be contrasted to sprinkle or drip irrigation where water is distributed over the field in pressurized pipes and then applied through sprinklers or drippers to the surface.

Surface irrigation has evolved into an extensive array of configurations which can broadly be classified as: (1) basin irrigation, (2) border irrigation, (3) furrow irrigation, and (4) wild flooding. The distinction between the various classifications is often subjective. For example, a basin or border system may be furrowed. Wild flooding is a catch-all category for the situations where water is simply allowed to flow onto an area without any attempt to regulate the application or its uniformity.   And since no effort is made to regulate the application or uniformity, this type of surface irrigation does not need attention in this handbook. If control of the wild flooding event is introduced, it then evolves into a border, basin or furrow system.

An irrigated field is only one component of an irrigation system as illustrated in Fig. I-1.
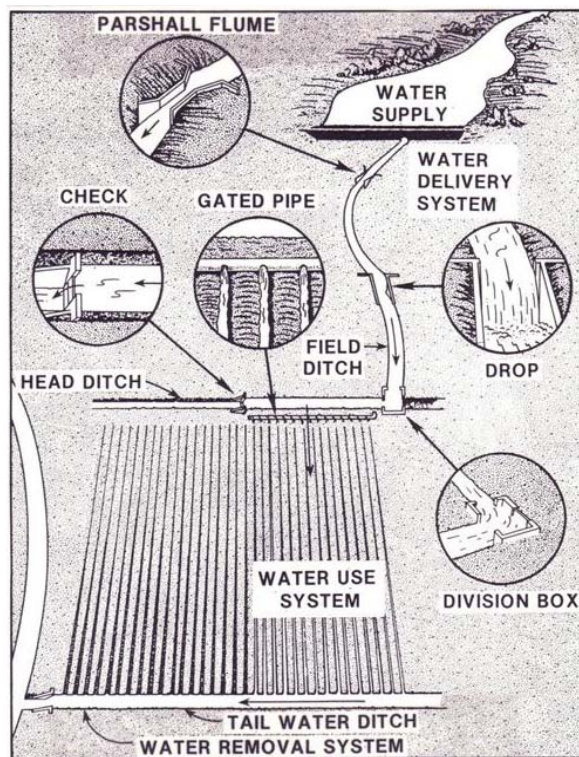
Figure I-1. Layout and function of irrigation system components.

Water must be *diverted* from a stream, *captured and released* from a reservoir, or *pumped* from the groundwater and then *conveyed* to the field. Excess water needs to be *drained* from the field. Each of these components requires *design*, *operation*, and *maintenance* of regulating and

control structures. In order for the system to be efficient and effective, the flow not only must be regulated and managed, but most importantly, it must also be *measured*. Thus, the on-field component (surface, sprinkle or drip), is the heart of the irrigation system. And, while it is necessary to limit the scope of this Chapter of the NRCS National Engineering Handbook to a guide for the evaluation and design of the surface irrigation system itself, it should be appreciated that the surface irrigation system is entirely dependent on the other components for its performance.

I.1.1   Surface Irrigation Processes

There are three general phases in a surface irrigation event: (1) advance; (2) wetting or ponding; and (3) recession. These are illustrated graphically in Fig. I-2. The ***advance phase*** occurs between when water is first introduced to the field and when it has advanced to the end. Between the time of advance completion, or simply advance time, and the time when water is shutoff or cutoff, is the period designated as the ***wetting or ponding phase***. The wetting or ponding phase will not be present if the inflow is terminated before the advance phase is completed – a typical situation in borders and basins but a rarity in furrows.

The wetting phase is accompanied by tailwater runoff from free-draining systems or by ponding on blocked end systems. After the inflow is terminated, water recedes from the field by draining from the field and/or into the field via infiltration. This is the ***recession phase***. All numerical models of surface irrigation attempt to simulate these processes.
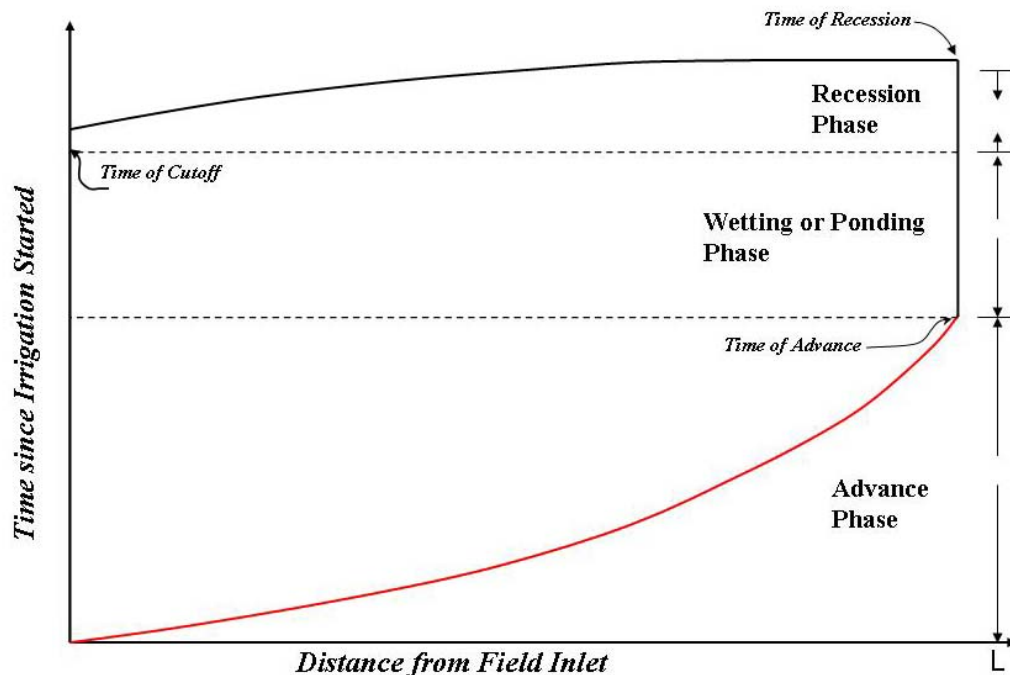
Figure I-2. The basic phases of a surface irrigation event.

I.2   SURFACE IRRIGATION CONFIGURATIONS

Choosing a particular surface irrigation system for the specific needs of the individual irrigator depends on the proper evaluation and consideration of the following factors: (1) costs of the system and its appurtenances, (2) field sizes and shapes, (3) soil intake and water holding

characteristics, (4) the quality and availability (timing of deliveries, amount and duration of delivery) of the water supply, (5) climate, (6) cropping patterns, (7) historical practices and preferences, and (8) accessibility to precision land leveling services.

I.2.1 Basin Irrigation

Basin irrigation is distinguished by a completely level field with perimeter dikes to control and/or prevent runoff. Figure I-3 illustrates the most common basin irrigation concept.

Figure I-3. Typical basin irrigation system in the western U.S.

I.2.1.1 Development Costs

Basin irrigation is generally the most expensive surface irrigation configuration to develop and maintain, but often the least expensive to operate and manage. Land leveling is the most costly development and maintenance requirement, although the perimeter diking can also be expensive to form and maintain. In areas where turnouts from the delivery system have relatively small discharges, development costs may also be increased by necessary changes in the irrigation system upstream of the basin.

Since basins are typically designed to pond the water on their surfaces and prevent tailwater, they are usually the most efficient surface irrigation configurations. In addition, management is almost always simpler.

I.2.1.2 Field Geometry

In the absence of field slope to aid the movement of water on the field surface, the "run length", or distance the water has to advance over the field tends to be minimized. Many basins

take on a square rather than a rectangular shape, but this depends entirely on the availability of sufficient flow rates and the intake characteristics of the soil.

One of the major advantages of basins is their utility in irrigating fields with irregular shapes and small fields.

I.2.1.3 Soil Characteristics

Basin irrigation systems usually operate at less frequent intervals than furrows or borders by applying a larger depth during irrigation. Consequently, medium to heavy soils with their high moisture holding capacity are better suited to basins than lighter soils. The efficiency and uniformity of basin irrigation depend on the relative magnitude of the field inflow and the soil intake. A soil with a relatively high intake characteristic will require a substantially higher flow rate to achieve the same uniformity and efficiency as for a heavier soil.

Since the water may cover the entire basin surface, a soil that forms dense crusts upon drying may have detrimental impacts on seed germination and emergence. It is common practice to furrow soils of this nature to reduce crusting problems. On the other hand, basin irrigation is an effective means for reclamation and salt leaching.

Many of the heavier soils will form cracks between irrigations which may be responsible for much of the water that infiltrates during irrigation. These soils are also susceptible to forming compacted layers (hard pans or plow pans) at the cultivation depth. The impact of cracking in basin irrigation is an increased applied depth while the impact of a "plow pan" is to restrict it.

I.2.1.4 Water Supply

The water supply to an irrigated field has four important characteristics: (1) its quality; (2) its flow rate; (3) its duration; and (4) its frequency of delivery.

The quality of the water added to the field will be reflected in the quality of the water throughout the root zone. Salinity is usually the most important quality parameter in surface irrigation and the higher the salinity in the irrigation water the higher will be the concentration of salts in the lower regions of the root zone. However, since basins do not apply water to the crop canopy as does sprinkle irrigation, water supplies with relatively high salinities can be used Some water supplies also have poor quality due to toxic elements like Boron. .

The most important factor in achieving high basin irrigation uniformity and efficiency while minimizing operational costs is the discharge applied to the field. In basin irrigation, the higher the available discharge the better, constrained only by having such a high flow that erosion occurs near the outlet.

The duration of irrigation is dependent on the depth to be applied, the flow rate onto the field, and the efficiency of the irrigation. Basin irrigation's typically high discharges and high efficiencies mean that basin irrigations may require less total time than borders and furrows. This coupled with the fact that basins usually irrigate heavier soils and apply larger depths means that the irrigation of basin is typically less frequent than borders or furrows. The duration and frequency of basin irrigation impose different requirements on the water supply system than systems operated to service border and furrow systems.

I.2.1.5 Climate

Whenever water ponds on a cropped surface for an extended period of time the oxygen-carbon dioxide exchange between the atmosphere and the roots is disrupted. If the disruption is long enough, the crops will die. This process is sometimes called "scalding". Scalding is perceived as a serious risk in basin irrigation by irrigators in hot dry climates. Of course rice farming depends on this process for weed control.

Another climate related impact of basin irrigation is the effect of water temperature on the crop at different stages of growth. Irrigation with cold water early in the spring can delay growth whereas in the hot periods of the summer it can cool the environment – both of which can be beneficial or detrimental in some cases.

One important advantage of basins in many areas of high rainfall is that they can more effectively capture it than can borders or furrows. Thus basins enjoy the benefits of higher levels of effective precipitation and may actually require less irrigation delivery during rainy periods as long as the crops are not damaged by subsequent scalding or flooding.

I.2.1.6 Cropping Patterns

With its full wetting and large applied depths, basin irrigation is most conducive to the irrigation of full-stand crops like alfalfa, grains, grass, and rice. Row crops can be and often are grown in basins as well. Widely spaced crops like fruit trees do not require as much of the total field soil volume to be wetted and thus basin irrigation in these instances is less useful. Although it should be noted that mini-basins formed around each tree and then irrigated in pass-through or cascade fashion are found in many orchard systems. Cascading systems are usually less efficient and have low uniformity due to poor water control.

Basin irrigation is also more effective with deep rooted crops like alfalfa than with shallow rooted crops like vegetables. Crops which react adversely to crown-wetting do not favor basins.

I.2.1.7 Cultural Factors

Because surface irrigation depends on the movement of water over the field surface, whose properties change from year to year and crop to crop as well as from irrigation to irrigation, surface irrigation management is a difficult task to do well and consistently. Basin irrigation reduces this burden by eliminating tailwater from the management process. However, where basin irrigation has not been practiced previously, the added costs and the uncertainty associated with a lack of experience are often substantial barriers to its adoption.

Basin irrigation is less common in the US than either border or furrow systems but has been shown to have significant advantages. Nevertheless, most irrigators will stay with practices that have been used previously in their area rather than take the risk associated with a new technology. Consequently, demonstrations are often necessary to introduce basin irrigation.

One of the criticisms of basin irrigation when used with square fields is the increased equipment turns during cultivating, planting, and harvesting operations.

I.2.1.8 Land Leveling

Before the advent of the laser guided land grading equipment, it was common to find surface elevations as much as one or two inches lower or higher than the design elevations of the

field. Land leveling operators varied in skill and experience. Today, the precision of land grading equipment is much greater and does not depend nearly as much on operator skill and experience.

It should come as no surprise that since the field surface must convey and distribute water any undulations will impact the flow and therefore the efficiency and uniformity. Basin irrigation is somewhat less dependent on precision field topography than either furrow or border systems because of high flows or the ponding, but many users of basin irrigation insist that the most important water management practice they have is "lasering". Precision land leveling is an absolute prerequisite to high performance surface irrigation systems, including basins. This includes regular precision maintenance during field preparations (land smoothing).

I.2.2   Furrow Irrigation

Furrow irrigation is at the opposite extreme of the array of surface irrigation configurations from basins. Rather than flooding the entire field, small channels called furrows and sometimes creases, rills, or corrugations are formed and irrigated as shown in Fig. I-4. The amount of water per unit width on a furrow irrigated field may only be 20% of the water flowing over a similar width in a basin. Infiltration is two-dimensional through the wetted perimeter rather than a vertical one-dimensional intake. Furrows can be blocked at the end to prevent runoff but this is not a common practice unless they are used in basins or borders to compensate for topographical variation or provide a raised seed bed to minimize crusting problems. The distinction between a furrowed basin or a furrowed border and furrow irrigation lies in the semantic preference of the user. For purposes of evaluation and design, both of these situations would fall under the term furrow irrigation.

Figure I-4. Furow irrigation using siphon tubes from a field bay.

I.2.2.1 Development Costs

Furrow irrigation systems are the least expensive surface irrigation systems to develop and maintain primarily because minimal land leveling is required to implement a furrow system and less precise land smoothing is necessary for maintenance. The furrow themselves can be formed with cultivation equipment at the time of planting.

While less expensive to implement, furrow systems are substantially more labor intensive than basins. Variations in individual flows, slopes, roughness, and intake alter the advance rate of each furrow and there are often substantial differences in how long it takes the water to reach the end of the furrow. In addition, some furrows are compacted by the wheel traffic of planting and cultivation equipment and have substantially different characteristics than non-traffic furrows. Irrigators compensate by adjusting the furrow flows and thereby need to be at the field longer. Further, they also have to assess how long to allow the water to run off the field before shutting it off as opposed to shutting the flow off in a basin when the correct total volume has been added to the field.

Because most furrow systems allow field tailwater, they are seldom as efficient as basin systems and thereby require more water per unit area. Measures such as the capture and reuse of tailwater can be employed to increase efficiency. Another alternative is a concept called ***cutback*** that involves reducing the furrow inflow after the flow has reached the end of the furrow. Surge flow and cablegation systems are examples of automated cutback systems.

I.2.2.2 Field Geometry

Furrow irrigated fields generally have slopes in both the direction of the flow and the lateral direction. These slopes can vary within a field although the slope in the direction of flow should not vary significantly unless it is flattened at the end of the field to improve uniformity. Figure I-5 illustrates the use of contour furrows to irrigate irregularly sloped fields. One of the major advantages of furrow irrigation is that undulations in topography have less impact on efficiency and uniformity than they do in either basin or border irrigation.

Figure I-5. Contour furrow irrigation.

I.2.2.3 Soil Characteristics

Furrow irrigation can be practiced on nearly all soils but there are two important limitations. First, the risk of erosion is higher in furrow irrigation than in either basin or border irrigation because the flow is channeled and the flow velocities are greater. Secondly, since the furrow actually wets as little as 20% of the field surface (depending on furrow spacing), applying

relatively large depths of irrigation water in the heavy soils can require extended periods of time and will result in low efficiencies. A four or six inch irrigation application is common in basin and border irrigation but would not be feasible with a furrow system on a particularly heavy soil.

Furrow irrigation is more impacted by soil cracks than borders and basins since the cracks often convey flow across furrows. Furrows are probably less impacted by restrictive layers due to their inherent two-dimensional wetting patterns.

I.2.2.4 Water Supply

Since the flow on the field is substantially less than in a basin or border system, a major advantage of furrow irrigation is that it can accommodate relatively small delivery discharges per unit area. As furrows typically apply smaller depths per irrigation, the availability of the delivery must be more frequent and for longer durations. More water on a volumetric basis is required for furrow irrigation because of its lower application efficiency in most cases.

Salts can accumulate between furrows and therefore the quality of irrigation water is more important in furrow systems than in basins or borders.

I.2.2.5 Climate

The climate over a surface irrigated field does not have significant impacts on the furrow irrigation. Scalding is seldom a problem even when the furrow ends are blocked. High winds can retard the furrow advance but this is rarely a problem. The effect of water temperature is less in furrows than in borders or basins because the wetted area is less.

I.2.2.6 Cropping Patterns

Furrows are ideally suited for row crops of all kinds but are also used in solid plantings like alfalfa and grains. When the seed bed is between furrows and must be wetted, it is necessary to apply water to the furrows for extended periods and efficiencies of these emergent irrigations can be very low. The lateral movement of water or "subbing", "wetting-across", etc. is a relatively slow process so many irrigators of higher value crops like vegetables use portable sprinkle systems for the emergent irrigations. Special crops like rice are generally not irrigated with furrows because of the need for a uniform submergence to control weeds.

I.2.2.7 Cultural Factors

Most of the cultural factors affecting furrow irrigation are the same as those noted previously for basin irrigation. The higher labor requirements require a resource in US agriculture that is becoming critically short. The lower efficiencies are problematic in an era of diminishing supplies, competition by urban needs, and the detrimental impact of salts and sediments on the quality of receiving waters when efficiencies are low. When polypipe is used to distribute water to the furrows an environmental concern with its disposal is raised. On the other hand, furrow irrigation is more flexible than either borders or basin as the configuration is easily changed by simply increasing or decreasing the number of furrows being irrigated simultaneously or by irrigating alternate furrows.

I.2.2.8 Land Leveling

While precision land leveling is not as critical to furrow irrigation as it is to basin and border irrigation, an irrigator cannot expect to achieve high uniformities and efficiencies without

it. Precision land leveling will reduce the furrow to furrow variations in advance times and will improve both uniformity and efficiency. Land leveling for furrow systems is also much less intrusive since field slopes can run in both field directions thereby reducing the volume of soil that has to be moved. Land smoothing, while not as important, is nevertheless a good practice on a regular basis.

1.2.3 Border Irrigation

Border irrigation looks like basin irrigation and operates like furrow irrigation. Figure I-6 illustrates a typical border irrigation system in operation. Fields may have a slope along the traditionally long rectangular fields but cannot have a cross-slope. The flow covers the entire surface and may be blocked at the downstream end to prevent runoff. Borders can also follow the contour lines in terraced fields as shown in Fig. I-7.

Figure I-6. Border irrigation in progress.
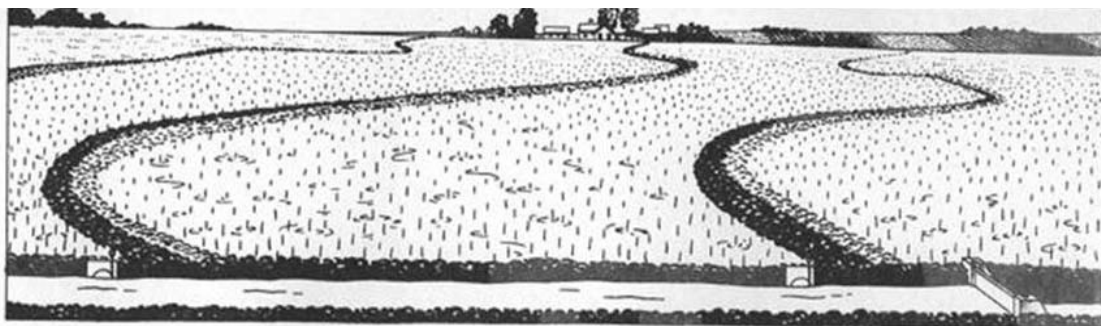
Figure I-7. Illustration of contour border irrigation.

I.2.3.1 Development Costs

The two major development costs for borders are land leveling and border construction. Land leveling is more extensive than for furrows and less extensive than for basins, particularly if the field is leveled along the existing slope in the direction of flow. The border dikes do not have to be as high as for basins but do need to be maintained in order to prevent cross-flow into

adjacent borders and care should be taken to intercept the flow that can occur in the dead furrow created by the diking equipment.

Borders do not generally require as much labor as furrow irrigation but do require more than for basins since the time of cutoff has to be judged properly. In fact, furrow system cutoff times are usually after the completion of advance and for borders, they are typically shorter and before the completion of the advance phase. Consequently, achieving high efficiencies is more difficult in border irrigation than in furrow irrigation. Traditionally, free draining borders have about the same efficiency and uniformity as furrows thereby reducing the economic feasibility of borders that allow tailwater. However, borders can also be blocked to prevent runoff and achieve efficiencies as high as those for basins thereby becoming slightly more economical than basins.

I.2.3.2 Field Geometry

Borders are usually long and rectangular in shape. Often referred to as "border strips", borders contain the flow within side dikes to direct the flow over the field. Borders can be furrowed where necessary for elevating a seed bed or compensating for micro-topography within the border. Borders can also be level or nearly level making them effectively the same as basins. Distinguishing borders from basins is often based on the rectangular shape rather than slope and in any event the differences are only semantic.

I.2.3.3 Soil Characteristics

Borders do not generally have erosion problems except near outlets and tailwater drains so they are somewhat more flexible irrigation systems than furrows. The slope aids advance and recession so border irrigation can be applied to the full range of soils so long as the flow per unit width is selected properly. However, as with basins, borders are better suited to the heavier soils and crusting soils may require special care such as furrowing.

I.2.3.4 Water Supply

Typical water applications under border irrigation are similar to basin systems and usually larger than furrows. In general border systems require 3-5 times as much flow per unit width as furrow systems and somewhat less than basins. For example, it would not be unusual to irrigate furrows on a spacing of at 2.5 feet with a 15 gpm flow (6 gpm/ft) and to irrigate a border with the same soil with a flow of 20 gpm/ft. The same water quality constraints noted for basins apply to borders as well. Consequently, water supplies for borders should be relatively high discharges for relatively short durations on relatively long intervals.

I.2.3.5 Climate

Scalding is a more serious problem in blocked end borders than in basins because the end depths are greater and require longer to drain from the field. It is common practice to provide blocked end borders with surface drainage capability in case an error is made in the time of cutoff and too much water ponds at the end of the field. Figure I-8 shows one of these end drains in a border irrigated alfalfa field.

Figure I-8. Tailwater outlet for a blocked-end border system.

In areas of high rainfall, ponding and subsequent scalding may be a problem without a surface drainage capability. And, the timing of irrigations in these areas is a critical issue. If irrigation is completed immediately prior to a large rainfall event, water may pond at the lower end and therefore the scalding potential might be substantial.

I.2.3.6 Cropping Patterns

Borders are used to irrigate most solid planting crops, and if furrowed, many row crops as well. Widely spaced trees are usually not irrigated with borders unless the borders enclose the tree line and leave an empty space between tree rows. And rice is not grown in borders. Since the water ponds the entire surface, crops with sensitivity to scalding may not be well irrigated with borders. Likewise, borders are better suited to deeply rooted crops like alfalfa than shallow rooted crops like vegetables.

I.2.3.7 Cultural Factors

Many growers like two things about borders – the long travel lengths for their machinery operations and the slope to facilitate the application of water during the initial wetting. These advantages are offset by more labor and management than for basins. Properly designed and managed, blocked end borders will have the same high efficiencies and uniformities as basins. Leaching is better in borders than in furrows but not as good as in basins.

I.2.1.8 Land Leveling

Precision land leveling is just as important to high performance in border irrigation as it is for either basins, where the ponding can compensate for some micro-topography, or furrows, where the channeled flow will keep the water from concentrating in one location of the field. With precision land grading a border flow will advance uniformly to the end of the field and apply a uniform and efficient irrigation. Land smoothing to maintain the surface profile is also important.

One of the interesting features of borders as with furrows is that the field slope does not need to be the same. In some heavy soils, the slope can be flattened over the lower 25% of the border to increase uniformity at the end of the field.

I.2.4   Summary of Surface Irrigation Methods

Choosing one type of surface irrigation over another is very subjective because of the number of criteria to consider and the complicated interactions among the criteria. Table I-1 below gives a general summary of the discussion above and some typical comparsions.

TABLE I-1. A GENERAL COMPARISON OF SURFACE IRRIGATION METHODS.

Selection Criteria	*Furrow Irrigation*	*Border Irrigation*	*Basin Irrigation*
Necessary Development Costs	Low	Moderate to High	High
Most Appropriate Field Geometry	Rectangular	Rectangular	Variable
Amount and Skill of Labor Inputs Required	High labor and high skill required	Moderate labor and high skill required	Low labor and moderate skill required
Land Leveling and Smoothing	Minimal required but needed for high efficiency. Smoothing needed regularly	Moderate initial investment and regular smoothing is critical	Extensive land leveling required initially but smoothing is less critical if done periodically
Soils	Light to moderate texture soils	Moderate to heavy textured soils	Moderate to heavy textured soils
Crops	Row crops	Solid-stand crops	Solid-stand crops
Water Supply	Low discharge, long duration, frequent supply.	Moderately high discharge, short duration, infrequent supply	High discharge, short duration, infrequent supply
Climate	All, but better in low rainfall	All, but better in low to moderate rainfall	All
Principal Risk	Erosion	Scalding	Scalding
Efficiency and Uniformity	Relatively low	High with blocked-ends	High

I.3   *WATER MANAGEMENT IN SURFACE IRRIGATION SYSTEMS*

Surface irrigation is difficult to manage at consistently high levels of performance (efficiency and uniformity) because the basic field characteristics change from irrigation to irrigation, crop to crop, and year to year. For example, the soil intake changes dramatically between the first irrigation following cultivation and the next. The field is also smoother so long as the crops do not grow in the flow path, but will become rougher as the season progresses

when they do. These variations cause the water to not only infiltrate at different rates but also change how fast the water advances over the field and recedes from it after the flow is turned off. If an irrigator misjudges the behavior of the system, the performance will decline. It is not surprising that surface irrigation efficiencies worldwide are low.

At the appraisal, design, or rehabilitation stage, the essential questions to be asked about the surface irrigation system are what kind of surface system should be selected, what unit flows to choose, when to turn the inflow off, what the field slope should be as well as its length, what structures and facilities are needed, and what should be done about tailwater if the field is to allow it? At the operational stage, the questions are what the unit flow should be and when it should be shut off? In other words, water management in surface irrigation systems involves both design and operational questions that involve the same set of parameters. The following are some general guidelines. More specific tools will be presented in subsequent sections.

I.3.1   Choosing a Surface Irrigation System

The eight factors discussed under basin, furrow, and border irrigation above will generally dictate the type of surface system that should be employed in a particular situation, but the irrigation specialist, advisor, or extension agent should not be surprised if it is not the last factor, a cultural factor, that is the deciding factor. The crops to be irrigated may determine the system immediately. For instance, if paddy rice is the major crop, basins will nearly always be the logical choice. Not always however. Some rice areas in the southern US prefer low-gradient, blocked-end borders to facilitate drainage and to better accommodate second crops like corn.

Future water quality goals for watersheds may be such that the surface irrigation systems must have a higher efficiency than can be achieved with furrows and therefore dictate basins, blocked end borders, or furrow systems with tailwater reuse. In many cases there may not be a definite advantage associated with any form of surface irrigation. The system selected must be based on farmer preference, cropping pattern, or environmental constraints.

Land leveling is nearly always the most expensive operation on the field itself and choosing a border or basin system over a furrow system must consider these capital costs in lieu of the savings in operational costs like water, labor and maintenance that emerge over a period of years. Consequently, leveling costs are probably the first indicator. Consider for example a field that would require $300 per acre to level it for basins. If the water cost is $15 per acre-foot, a not unusual figure, it would require many years to recapture the investment costs of the leveling with water savings alone. On the other hand if labor is critically expensive and short, perhaps the basins would be a more feasible choice. In short, if a change in surface irrigation system is contemplated, examining the leveling costs after considering cultural factors will prove useful.

I.3.2   Inlet Discharge Control Practices

There is an interesting trade-off between the inflow rate and the time of cutoff which influence uniformity and efficiency differently. If the discharge per unit width is too small the water will advance very slowly over the field resulting in poor uniformity and low efficiency. The problems with uniformity will be due to the large differences in the time water is allowed to infiltrate along the field (intake opportunity time). Low efficiency is caused by intake exceeding the soil's ability to store it in the root zone of the crop (deep percolation). If the unit flow is

incrementally increased, both uniformity and efficiency will increase and this increase will continue in a positive manner for basin irrigation but not for border and furrow irrigation.

In free draining furrow and most border systems the incremental increase in unit discharge (with a corresponding decrease in cutoff time so the volume required is approximated) will reach a point where the efficiency reaches a maximum and begins to decline even as uniformity continues to increase. The cause of this peaking of efficiency is the gradual increase in field tailwater that will more than offset the decreases in deep percolation as uniformity improves.

One of the problems in surface irrigation is that the first irrigation of the season following planting or cultivation often requires two or three times the flow rate that subsequent irrigations need to achieve acceptable uniformity. The infiltration rates are higher during these "initial" irrigations and thus the need for higher inlet flows. As the soil intake diminishes during the season, the inlet flows can be reduced. Thus, the design and operation of surface irrigation systems requires adjusting the inlet flow and its duration to achieve maximum efficiencies.

I.3.3 Changing the Field Geometry and Topography

Cultivation, planting, and harvesting with modern US agriculture and its advanced mechanization are more efficient for large fields with long lengths of run. As the soil texture in a large field may range from clay and clay loam to silt loam and sandy loam, the length of the field may be too long for efficient surface irrigation. Dividing the field in half, thirds, or quarters is often an effective way to achieve better uniformities and efficiencies. However, because a field subdivision costs the farmer in mechanization efficiency, land area, and money for the changes, surface irrigation should be evaluated first using the field dimensions that correspond to property lines, organization of supply pipes or ditches, or what the farmer is currently doing.

Good design practice avoids slope changes unless necessary to change type of surface irrigation system. Surface irrigation can be configured to work well within a range of slopes between 0 and 0.5%. If a flatter slope is needed to control erosion at the end of a sloping field, flattening the last quarter of a field's slope is easily accomplished with modern laser guided land leveling equipment and need not be prohibitively expensive.

Surface irrigation performance can always be improved by accurate leveling and smoothing of the field surface. As noted previously, most irrigators consider precision land grading as the best water management practice.

Furrowing borders or basins also reduces the effect of topographical variations. Some soils are too coarse textured for efficient surface irrigation, but practices aimed at incorporating crop residues and animal manures not only change intake rates but also improve soil moisture-holding capacity. When water advance over a freshly cultivated field is a problem due to high intake, a limited discharge, or an erosion problem, the surface is often smoothed and compacted by attachments to the planting machinery.

I.3.4 Tailwater Recovery and Reuse

In order to convey water over the field surface rapidly enough to achieve a high degree of application uniformity and efficiency, the discharge at the field inlet must be much larger than the cumulative intake along the direction of advance. As a result, there remains a significant fraction of the inlet flow at the end of the field which will run off unless the field is diked or the tailwater is captured and reused. In many locations, the reason to capture tailwater is not so much for the value of the water but for the soil that has eroded from the field surface. Other

conditions exist where erosion is not a problem and the water supply is abundant, so the major emphasis is merely to remove the tailwater before waterlogging and salinity problems emerge. Finally, it may be cost-effective to impound the tailwater and pump it back to the field inlet for reuse or store it for use on lower-lying fields. A typical tailwater reservoir and pump-back system is shown in Fig. I-9.

Figure I-9. A typical tailwater recovery and reuse system.

I.3.5 Automation and Equipment

High labor requirements are a disadvantage of surface irrigation that many irrigators cite as reasons for converting to sprinkle or drip irrigation. Automation which can regulate the supply flow to various parts of the field and properly adjust unit flows and cutoff times is a critical need in surface irrigation. Unfortunately, experience to date has been mixed because a standard technology has not been developed for widespread use.

I.3.5.1 Border and Basin Facilities and Automation

Some of the common facilities for border and basin irrigation are shown in Fig. I-10. They include single gate offtakes, ditch gates, siphons, alfalfa valves, and simple check-dividers, to show a few options. The automation for basin and border involves mechanizing and controlling individual outlets and is comparatively straight forward for the single gate offtakes. For instance the jack gate shown in Fig. I-10 can readily be equipped with a remotely controlled actuator such as a pneumatic piston. Where water control involves siphons or ditch gates automation is generally impractical.

As a rule, automation of border and basin offtakes involves retrofitting mechanization to the gate, and then connecting it via wire, telephone, or radio to a controller where the irrigator can make remote changes or where regulation can be made of the system at specified time intervals. The wheel-actuated gate shown in Fig. I-11 can be equipped with a small electric motor and gear assembly to automate the offtake. In any event, whenever automation can be reduced to single gate as for many borders and basins, it is much more feasible and reliable than for furrow systems.

(slide gate)

(ditch gates)

(alfalfa valve)

(large diameter siphon tures)

Figure I-10. Typical border and basin field outlets.

(typical gate structure)
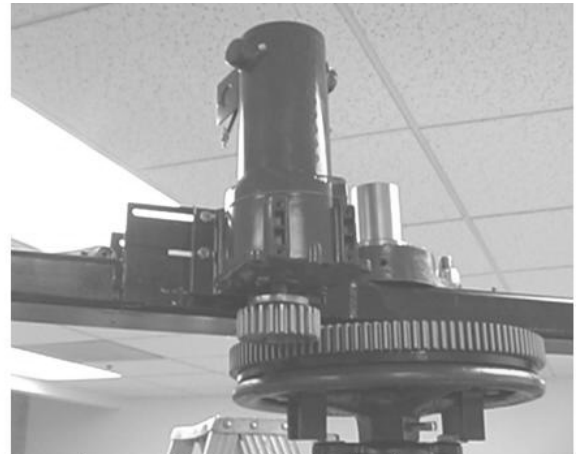
(gate with mechanization)

Figure I-11. A wheel lift slide gate before and after automation.

I.3.5.2 *Furrow Irrigation Facilities and Automation*

Furrows are often supplied water by some of the same facilities used in borders and basins. For example, shown in Fig. I-12 are two furrow systems supplied by ditch gates and siphon tubes.

Furrow ditch gates   Siphon tubes

Figure I-12. Two methods of supplying water to furrows.

Perhaps the most common furrow irrigation system is one using gated pipe. Two examples are shown in Fig. I-13 to illustrate both the rigid and flexible options. Rigid gate pipe is generally found in aluminum or pvc and range in size from 6-inch to 12-inches with gate spacings ranging from 20-48-inches. The flexible gated pipe, or polypipe, can be purchased in sizes from 12 to 18 inches with wall thicknesses of 7 - 10 mil. An advantage of flexible gated pipe is being able to place gates at any spacing desired. In fact, occasionally gates are not used at all, just holes punched in the pipe.

Figure I-13. Gate pipe options for furrow irrigation.

Furrow systems can also be served by "field bays" or narrow shallow channels at the head of the field that create a small reservoir from which individual furrows are supplied water. Figure I-4 presented earlier showed an example of this furrow irrigation configuration. In this case water is diverted from a head ditch into the field bay and then diverted into the furrows with siphons.

I.3.6 Cutback

In order to achieve the most uniform surface irrigation, the advance phase has to occur fairly quickly and to do so requires a relatively large unit flow. In border or basin irrigation the inflow is terminated in most cases before the advancing front reaches the end of the field. In furrow irrigation, however, it is nearly always necessary to maintain inflow well beyond the completion of advance in order to refill the root zone. Consequently the runoff or tailwater volume can be high and the efficiency low. One way of overcoming this problem is to allow a high flow during the advance phase and then reduce it to a smaller value during the wetting phase and thereby minimize tailwater. This is called "cutback". A simple example is the use of two siphons per furrow during the advance phase and then reducing the flow by eliminating one of the siphons during the wetting phase.

Furrow irrigation automation has not been very successful until the advent of the "surge flow" concept although systems like the "Cablegation" system developed in Idaho have proven to work well during field research and demonstration studies. Cablegation involves a mechanized "plug' attached to a cable which is extended at a fixed rate from the upper end of the system. The flows from gated openings near the plug have higher rates than those away from the plug and thus as the plug moves along the pipe the flow in the upstream furrows decrease. Figure I-14 shows a schematic of a typical Cablegation system. Cablegation is an interesting form of a more general concept called "cutback" irrigation. Cablegation has not found widespread use due to its complex hardware, difficult management requirements and lack of standardized and commercial equipment.
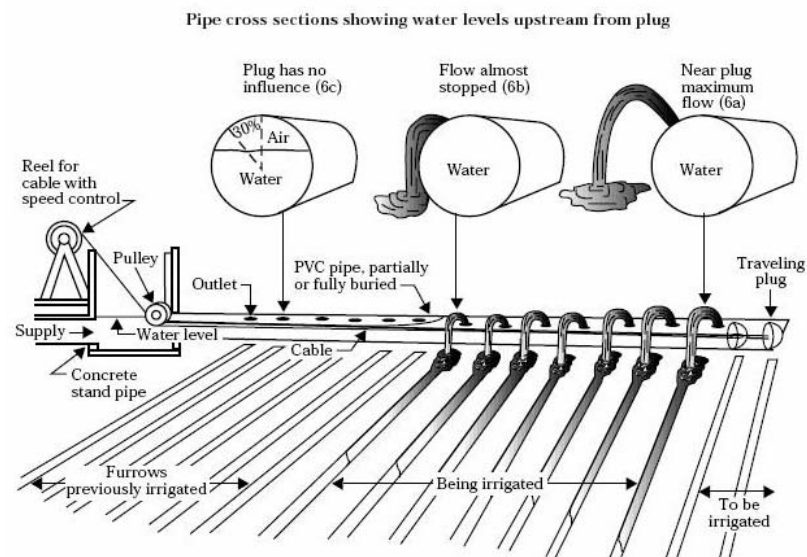
Figure I-14. Schematic Cablegation system.

As a concept, cutback is an attractive way to improve furrow irrigation performance. In practice, it is almost impossible to implement in the field and it is inflexible. Of course with simple furrow irrigation system using siphons it can be done with substantial labor. But since the advance time and wetting time need to be about equal, the savings in tailwater may be nearly offset by increases in deep percolation. In terms of automation, the practicable ways of implementing cutback are the Cablegation system or surge flow.

I.3.7 Surge Irrigation

Under the surge flow regime, irrigation is accomplished through a series of short duration pulses of water onto the field. A typical advance/recession plot for a surged system is illustrated in Fig. I-15. Thus instead of providing a continuous flow onto the field, a surge flow regime would replace a six hour continuous flow set with something like six 40-minute surges. Each surge is characterized by a cycle time and a cycle ratio.
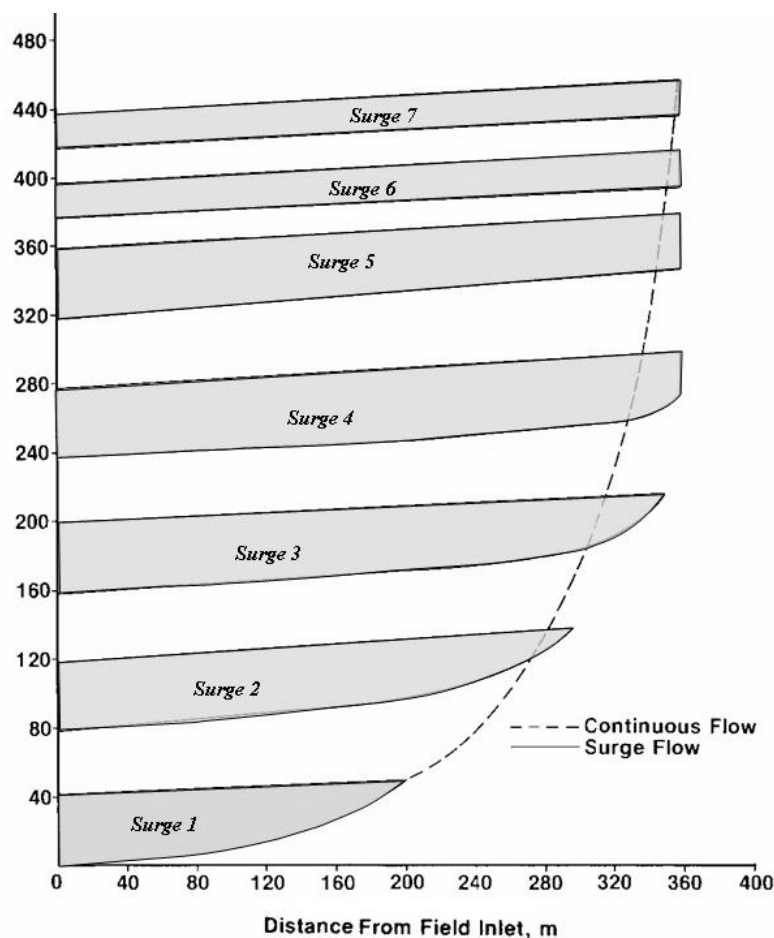
Figure I-15. Advance and recession trajectories for a surge flow system.

The cycle time is the sum of an on-time and an off-time which do not need to be equal. The ratio of on-time to the cycle time is the cycle ratio. Cycle times can range from as little as one minute during a cutback phase to as much as several hours in low gradient borders and basins. Cycle ratios typically range from 0.25 to 0.75. By regulating these two parameters, a wide range of surge flow regimes can be produced to improve irrigation efficiency and uniformity.

I.3.7.1 Effects of Surging on Infiltration

Since its introduction in 1979, surge flow has been tested on nearly every type of surface irrigation system and over the full range of soil types. Results vary depending on the selection of cycle time, cycle ratio and discharge. Generally, the intermittent application significantly reduces infiltration rates and thus the time necessary for the infiltration rates to approach the final or 'basic' rate. To achieve this effect on infiltration rates, the flow must completely drain from the field between surges. If the period between surges is too short, the individual surges overlap or coalesce and the infiltration effects are generally not created.

The effect of having reduced the infiltration rates over at least a portion of the field is that advance rates are increased. Generally, less water is required to complete the advance phase by surge flow than with continuous flow. Surging is often the only way to complete the advance phase in high intake conditions like those following planting or cultivation. As a result, intake opportunity times over the field are more uniform. However, since results will vary among soils, types of surface irrigation, and the surge flow configurations, tests should be conducted in areas where experience is lacking in order to establish the feasibility and format for using surge flow.

I.3.7.2 Surge Flow Systems

The original surge flow system involved automating individual valves for each furrow using pneumatic controls. One of the early systems is shown in Fig. I-16. The complexity and cost of these systems proved to be infeasible and a simpler system involving an automated butterfly valve like the one shown in Fig. I-17 was developed to implement surge flow by sequentially diverting the flow from one bank of furrows to another on either side of the value.

Figure I-16. Early surge flow system.

The automated butterfly valves have two main components, a butterfly valve and a controller. The valve body is an aluminum tee with a diverter plate that directs water to each side of the valve. The controller uses a small electric motor to switch the diverter plate and its type varies with its manufacturer. Most controllers can be adjusted to accomplish a wide variety of surge flow regimes. For instance, most controllers have both an advance stage and a cutback stage. During the advance stage water is applied in surges that do not coalesce and can be sequentially lengthened. Specifically, it is possible to expand each surge cycle so surges that wet the

downstream ends of the field are longer than those at the beginning of irrigation. During the cutback stage, the cycles are shortened so the individual surges coalesce.
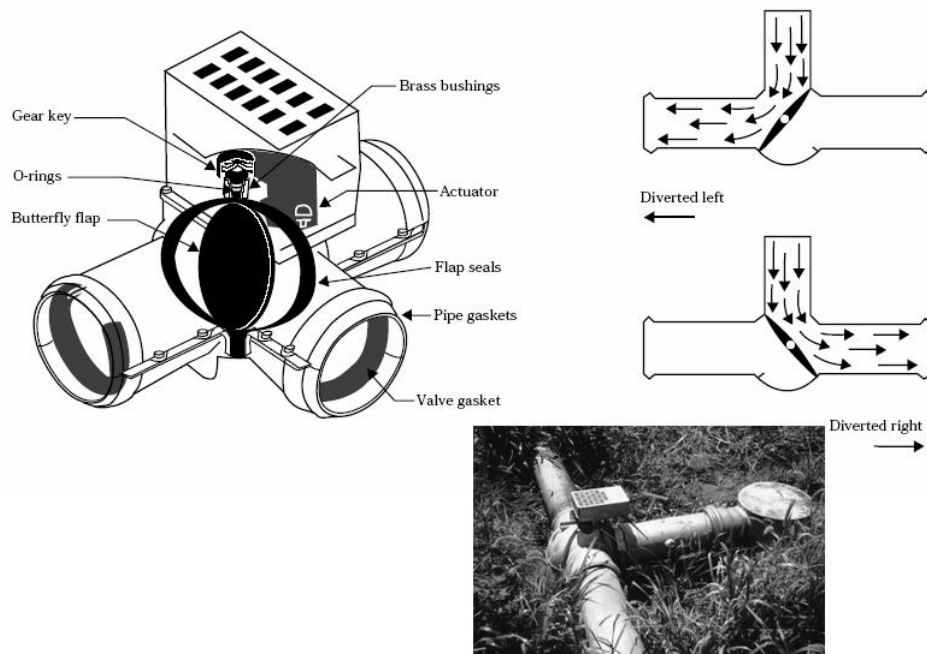
Figure I-17. The automated butterfly surge flow valve.

Adaptation for border and basin systems can be made by automating existing control structures and perhaps by a new control structure. Generally, the surge cycle time for these systems must be 2-4 times as long as in furrow systems to allow complete recession between surges.

II SURFACE -- NRCS Surface Irrigation Simulation, Evaluation, and Design Software

II.1 OVERVIEW

The practices of surface irrigation evaluation and design have changed significantly since the first publication of the SCS National Engineering Handbook, Section 15 *Irrigation*, Chapters 4 and 5 describing border and furrow irrigation. Two generations ago engineers relied on tables, nomographs, and slide rules to choose a flow and a field length. "Rules-of-thumb" led to choices of flow, length of run, and slope. A generation ago, the slide rule was replaced by programmable handheld calculators and computer models supplemented available tables and nomographs. Calculation of advance and recession trajectories allowed the irrigation specialist to more accurately evaluate uniformity and efficiency. Realistic assessments of the impact of changing flows, length, and slopes were possible. Today, the "personal computer" has replaced all of its predecessors. Information is "on-line" and "real-time". Rules-of-thumb are almost entirely unknown in current curricula, and very few graduating engineers have even seen a slide rule. Analyses now focus on hydrodynamic, zero-inertia, or kinematic wave models. Tomorrow, most of what is carried in a brief case will be carried in a shirt pocket. And perhaps, a new generation of biosensors will be available that will allow surface irrigation systems to be managed "on-line" and "real-time".

In recognizing the need to update Section 15, the NRCS also recognized the need to provide modern tools for simulating, evaluating, and designing surface irrigation systems. The NRCS *SURFACE* program was written to fulfill this need.

SURFACE is a comprehensive software package for simulating the hydraulics of surface irrigation systems at the field level, selecting a combination of sizing and operational parameters that maximize performance, and a convenient way to merge field data with the simulation and design components. The programming uses a 32 bit C++ language to encapsulate the numerical procedures which describe the "hydrodynamic" theory in general use today. The software has been written for "IBM compatible" micro or personal computer systems utilizing Microsoft Corporation's Windows 95 or later operating systems. This section provides the reader with a user's manual for the *SURFACE* program and some detailed data sets that demonstrate its use.

II.2 GETTING STARTED

SURFACE and its companion files can be obtained from your state irrigation specialist or IT personnel. The local IT person can provide help installing the program.

There are a number of files included in the package. These include the *NRCS_SURFACE.*EXE file, and several sample input data files with a *cfg* extension.

II.3 SPECIAL CONTROLS

The opening or main screen of *SURFACE* is shown above as Fig. II.1. Program controls can be accessed via either a set of speed buttons or a series of drop-down menus. A closer look at this part of the main screen is shown in Fig. II.2.

Figure II-1. The main *SURFACE* screen.
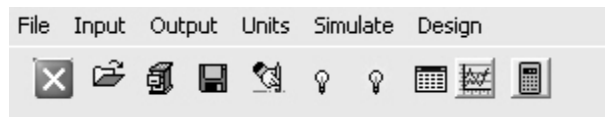
Figure II-2. The *SURFACE* command bar.

The *SURFACE* software can be run from the **Run** command of the Windows Start menu, by double clicking on *NRCS_SURFACE.EXE* from the Windows Explorer, or by clicking on a shortcut icon the user has created. In whatever case, the first program screen the user sees will be as shown above will involve four basic tasks: (1) inputting or retrieving data from a file; (2) manipulating data and storing them; (3) simulating the surface irrigation system described by the input data; and (4) viewing, storing, and printing results. In addition, there are two special cases provided in the software to manipulate data and/or simulations. The first is to derive infiltration parameter values from field measurements and the second is to simulate alternative system configurations as part of an interactive design feature. Both of these will be described separately below.

II.3.1 File Operations and Exiting *SURFACE*

The program and any window or screen object can be closed by clicking on the ⊠ buttons. The program itself can also be closed by clicking on the **File** menu selecting **Exit** as shown here.

Existing input files can be accessed through the open menu item under the **File** drop-down menu as shown or by clicking the speed button ☞ .
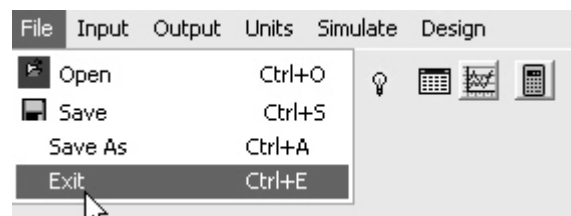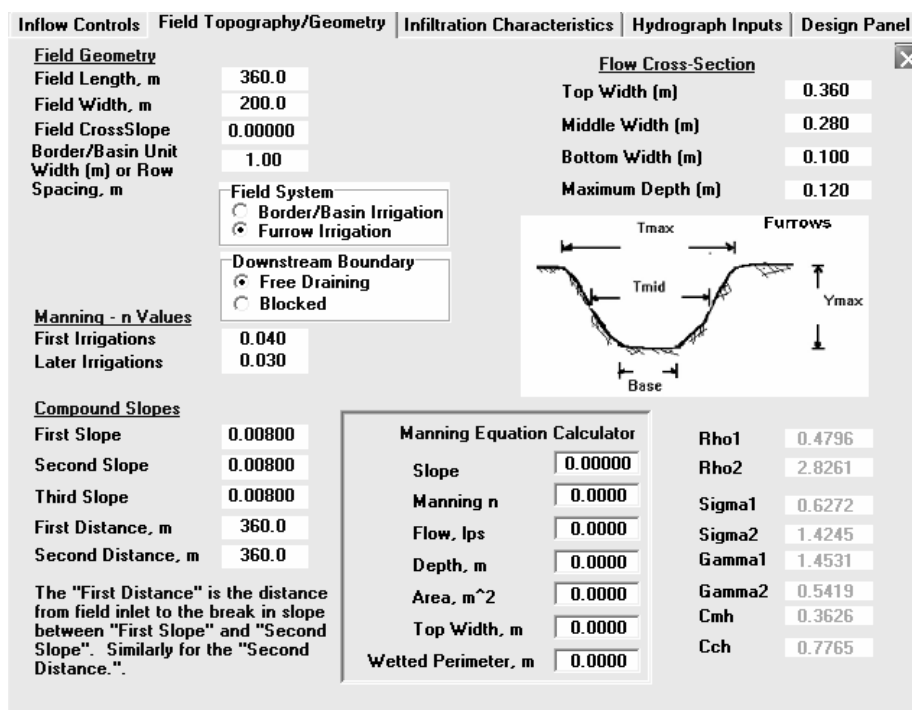
Once the user has finalized a set of input data, it should be saved to an existing or new file. Saving to an existing file can be accomplished from the **File** menu using the **Save** option or

by clicking on the save speed button ▣ . The **Save As** option from the **File** menu reveals a dialog box in which the user can save the data under a new file name.

II.3.2 Input

Both the **Input** menu and the speed button 🗇 are one click actions that will cause the input tabbed notebook to appear in the main screen as shown in Fig. II-3. Data can then be input and viewed.

Figure II-3. The *SURFACE* input tabbed notebook.

II.3.3 Output

The *SURFACE* software includes tabular as well as graphical presentation of simulation results. These options can be accessed from the main menu by clicking on **Output** and then choosing displayed (numerical) or plotted results.
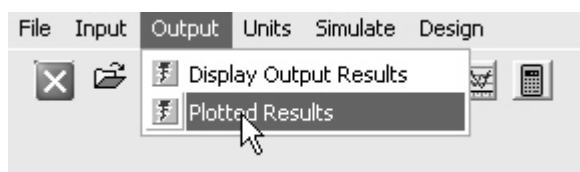
Two speed buttons are also available for displayed 🔲 and plotted 📈 results. Figure II-4 illustrates the displayed data window. Both will be discussed more in sections below.

II.3.4 Units

The input data and results of simulation, design, and evaluation can be displayed in metric or English units. This is a user selectable option accessed via the **Units** menu at the top of the main screen as shown here. Units may also

be selected from the "*Infiltration Characteristics*" panel in the input tabbed notebook.

Figure II-4. The *SURFACE* tabular output screen.

There are three options, two for English and one for a metric system of units. The default selection is English-gpm as shown. The selected system of units is stored with the input data file so each time the user loads the particular file those units will be displayed and used. Thus, the unit selection should be made before entering input data and/or before saving the input data file.

II.3.5 Simulation

The selection of **Simulate** on the main menu bar or the speed button [■] will cause the simulation programming to execute using whatever data are currently stored in memory. A number of safety checks are made to insure that the appropriate characteristics of the surface irrigation system are defined. The simulation programming utilizes a fully hydrodynamic analysis of the system. Input data options are provided to increase or decrease the execution speed to suit the visual appearance of the graphics screen that presents the simulation results time step by time step. A more detailed discussion of the simulation functions will be given later along with some example problems.

II.3.6 Design

The **Design** option on the main menu bar will open the input data tabbed notebook to the *Design Panel*. This can also be accessed through the input options noted earlier. The design programming allows the user to simulate and modify various design configurations in an interactive mode.

II.4 DATA INPUT

Providing input data to the *SURFACE* software involves two activities: (1) defining the characteristics of the surface irrigation system; and (2) defining the model operational control parameters.

The input tabbed notebook, shown earlier as Fig. II-3, can be accessed from the **Input** menu command or the speed button. The tabs are from left to right: (1) ***Inflow Controls***; (2) ***Field Topography and Geometry***; (3) ***Infiltration Characteristics***; (4) ***Hydrograph Inputs***; and (5) ***Design Panel***. Input data for the first three panels are required for all applications of the ***SURFACE*** software. The fourth, ***Hydrograph Inputs*** is an optional feature to allow field data inputs to the simulation programming. The ***Design Panel*** is only for interactive design functions and will be discussed separately.

II.4.1 Entering Field Characteristics

The first data the user may wish to define are those associated with the field topography and geometry. This panel is shown in Figure II-3 and repeated below in Fig. II-5 for the border/basin input.

Figure II-5. The Field Characteristics panel of the input tabbed notebook.

The geometry and topography of the surface irrigated field is described by inputting the following parameters:

Field length and width;
Field cross-slope;
Type of system (furrow or border/basin)
Unit spacing for borders and basins, or furrow spacing;[1]
Downstream boundary condition;
Manning roughness, **n**, for the first and later irrigations;
Three slope values in the direction of flow;

---

[1] Furrow spacing refers to the spacing between adjacent irrigated furrows. When alternate furrows are irrigated, an unused furrow lies between the irrigated furrows and is not considered in the definition of furrow spacing.

Two distance parameters associated with the three slopes; and
Four measurements of flow cross-section.

II.4.1.1   *Basic Field Geometry*

The basic geometry of the field includes its length or the distance water will run, its width and cross-slope, the type of surface irrigation system, a unit width or furrow spacing, and the nature of the downstream field boundary. The field's cross slope is not utilized in the software but is needed to design the headland pipes or ditches used to irrigate the field. These parameters are constant within each "field" and may not represent the entire area being irrigated.

The simulation program evaluates the hydraulics of the irrigation over a unit width. Typically, the unit width for border and basin simulation is one foot but can be other dimensions if desired. Whatever value that is selected must be consistent with the **Simulated Unit Flow**. In other words, if the unit width is 2.5 ft, the simulated unit flow must be the discharge onto the border or basin that flows within this width.

If the system is configured for furrows, the simulation evaluates the flow in a single "average" furrow.

II.4.1.2   *Manning n*

One of the most important considerations in surface irrigation evaluation and design is the changes that occurs on the field surface as it is irrigated. Newly tilled soil is usually hydraulically "rougher" than soil surfaces that have been smoothed by the flow of water during irrigation. On the other hand, surfaces such as borders and basins may become hydraulically rougher as crop density and size increase.

The *SURFACE* software includes the feature necessary to examine two field conditions which are noted as first irrigation and later irrigation conditions. In order to perform the various simulations, the software requires input of two estimates of the Manning n coefficient for these two conditions.

Freshly constructed furrows typically have *n* values of about 0.03-0.05 depending on the soil aggregation. Previously irrigated furrows without crops growing in the furrow itself will have substantially lower *n* values. Measurements have been reported where these *n* values have been as low as 0.015. In the absence of more detailed information, it is probably sufficient to use an *n* value of 0.04 for first irrigations and 0.02 for later irrigations, but the user has an opportunity to apply judgment here where necessary.

The Manning *n* values for borders and basins vary over a much wider range than they do for furrows, primarily because they are affected by the crop and the geometry of its crown. A freshly tilled and prepared border or basin with a bare soil surface probably has an *n* value about the same as for furrows, 0.03-0.05. After initial irrigations and before substantial crop growth, the *n* value may be as low as 0.15-0.02, but later as the water is impeded by the crop, the *n* values can be as high as 0.80 for a crop like an alfalfa-grass mix. The *SURFACE* software can be used in conjunction with field measurements of advance and recession to estimate the *n* values and this will be described later.

II.4.1.3   *Field Slope*

The *SURFACE* software is capable of simulating fields with a compound slope as shown in Fig. II.6. Up to three slopes can be located in the field by two distance values. When the field

has only one slope, the same value needs to be entered for all three slopes and both distance values should be set to the field length. A field with two slopes can be defined by setting the second and thirds slopes to the same value and the second distance to be the difference between the field length and the first distance.
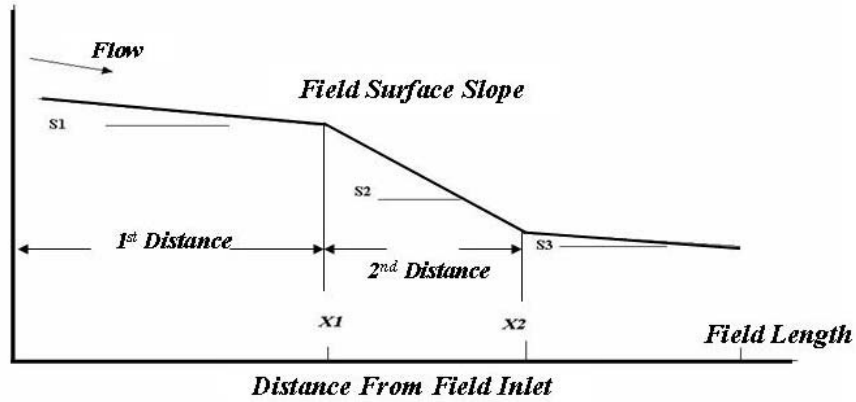
Figure II-6. Illustration of multiple sloped surface irrigated field.

II.4.1.4 *Flow Cross-Section*

The flow cross-section is defined and computed with four parameters, top width, middle width, base, and maximum depth. As these are entered eight parameters labeled Rho1, Rho2, Sigma1, Sigma2, Gamma1, Gamma2, Cch, and Cmh are automatically computed. It is important that the four dimensions required in the input screen are those that are associated with the unit discharge for border and basins or per furrow for those systems. If the **Field System** selected is a border or basin, the values of top width, middle width, and bottom width are the same and equal to the unit width.
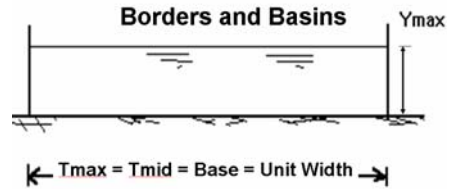
The values of **Rho1 (ρ_1)**, **Rho2 (ρ_2)**, **Sigma1 (σ_1)**, **Sigma2 (σ_2)**, **Gamma1 (γ_1)**, **Gamma2 (γ_2)**, **Cch**, and **Cmh** are based on the following relationships:

$$WP = \gamma_1 y^{\gamma_2}$$

$$A = \sigma_1 y^{\sigma_2}$$

$$A^2 R^{4/3} = \rho_1 A^{\rho_2}$$

$$\rho_2 = \frac{10}{3} - \frac{4\gamma_2}{3\sigma_2} \tag{II-4}$$

$$\rho_1 = \frac{\sigma_1^{10/3-\rho_2}}{\gamma_1^{4/3}} \tag{II-5}$$

$$T = (Cch)\, y^{Cmh} \tag{II-6}$$
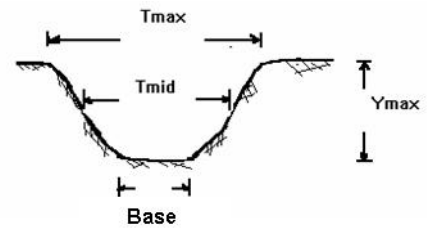
The parameters **WP**, **A**, **y**, **R**, and **T** are the flow cross sectional wetted perimeter, cross-sectional area, depth, hydraulic radius, and surface top width, respectively. For borders and basins in which the unit width is b feet, the values of the respective parameters are: $\gamma_1=b;$ $\gamma_2=0;$ $\sigma_1=b;$ $\sigma_2=1;$ $\rho_1=b^2;$ $\rho_2=10/3$, Cch =b; and Cmh=0. For furrows, these parameters take on many values and need to be computed from the cross-sectional measurements of T_{max}, T_{mid}, **Base**, and Y_{max}. The **SURFACE** program does this by numerically integrating the furrow shape.[2]

On the lower center of the **Field Topography/Geometry** notebook is a Manning flow calculator shown here. Once the basic shape has been defined by the unit width for borders or T_{max}, T_{mid}, **Base**, and Y_{max} for furrows, the user can enter a slope, a Manning **n** and a flow. The Manning calculator will then compute the depth of flow, the cross-sectional area, depth and wetted perimeter. Or the user can enter the slope and Manning **n** along with any one of the other variables such as area and the remaining others will be determined. The Manning calculator will assist the user in evaluating border and dike heights, checking whether or not the furrow has overflowed due to the flow or blocked end, or to determine what the maximum flow could be without breaching the border dikes or furrow perimeters.

Manning Equation Calculator	
Slope	0.00800
Manning n	0.0400
Flow, gpm	32.0000
Depth, ft	0.2376
Area, ft^2	0.0924
Top Width, ft	0.6348
Wetted Perimeter, ft	0.8262

The Manning calculator can also be used to approximate the conditions in open channel field ditches. It should be noted that the procedures were written for irregular shapes like typical furrows and are only approximate for the regular trapezoidal shapes. To use the calculator or field ditch evaluation and design, set the "**Field System**" to furrows by checking the appropriate box. Then in the "**Flow Cross Section**" boxes enter the channel shape. Finally, move the cursor to the Manning calculator and enter the respective parameters.

II.4.2 Infiltration Characteristics

The tabbed notebook where infiltration functions are defined is shown in Fig. II.7. These data comprise the most critical component of the **SURFACE** software. Four individual infiltration functions can be defined: (1) a function for first conditions under continuous flow; (2) a function for later irrigations under continuous flow; (3) a function for first irrigations under surge flow; and (4) a function for later irrigations under surge flow. The user is referred to Section III for a detailed discussion of how these parameters are defined and measured, but they are important enough to be given further attention here. Note that the model does not allow a cracking term for surge flow since it is assumed the cracks will close during the first surge on the dry soil portion of the field.

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[2] The values of **Cch, γ_1, σ_1,** and **ρ_1**, also depend on the units used. The **SURFACE** software only displays the metric values even when English units are used for input.

Figure II-7. The Infiltration Characteristics panel of the input tabbed notebook.

Just below the four intake parameters are two boxes labeled ***Qinfilt, gpm*** which are used to enter the flow at which the intake parameters are defined. Furrow intake parameters are always defined for a unique flow whereas border and basin parameters are not. The ***SURFACE*** software uses the values of ***Qinfilt*** to adjust furrow intake parameters for changes in flow. Note that ***Qinfilt*** boxes are not provided for the surge flow conditions as they must be the same as the respective continuous flow value. In other words, the ***Qinfilt*** value for the initial surge flow condition is assumed to the same as that for the initial continuous flow condition.

It is not necessary to define infiltration for each of the four conditions. However, they must be defined for the cases the user wishes to simulate, evaluate, or design by having checked the boxes next to the **Simulate** label. Specifically looking at the figure below, if the user is interested in only simulating the initial continuous flow, then the values necessary are just in that column. If surge flow is to be evaluated, the intake coefficients are necessary in the first and third columns. By changing the check box selections, the user can simulate later irrigation conditions

as well. The surge flow check boxes are deactivated since it is necessary for the simulation of an initial surge flow or later surge flow condition that the associated continuous flow intake be used for the flow of water over the dry portion of the field.

The ***SURFACE*** software includes sets of values for *a*, *k*, f_o, and *c* (or *a*, *K*, F_o, and *C*) which can be accessed by clicking on one of the [Tables] buttons. The intake functions represented are based on the original USDA-SCS intake families modified to be consistent with

for the intake equations used in the **SURFACE** software (See Section III.2.2). Figure II-8 show one of these tables for a furrow system. A set of values can be selected by clicking on the associated radio button on the left of the table.   The corresponding values will then be automatically entered in the boxes of Figure II-7. The c or C values are terms to adjust for large field cracks and may be set to zero. The value of f_o and F_o are basic or long tern intake rates and may be set to zero for short irrigation events which are typical for borders and basins but generally not so for furrows. The k or K and a parameters should always be defined.

Continuous Flow Intake Curve Parameters for Initial Irrigations

ID	Soil Name	a	K (ft^3/ft/mn^a)	Fo (ft^3/ft/mn)	Qr (gpm)	Wpr (ft)
.02	Heavy Clay	0.1880	0.002420	0.0000786	7.41	0.365
.05	Clay	0.2488	0.004466	0.0001981	8.26	0.399
.10	Clay	0.3067	0.006823	0.0003369	9.65	0.452
.15	Light Clay	0.3517	0.008710	0.0004704	11.02	0.500
.20	Clay Loam	0.3878	0.010346	0.0005974	12.38	0.544
.25	Clay Loam	0.4175	0.011807	0.0007212	13.72	0.586
.30	Clay Loam	0.4427	0.013140	0.0008396	15.04	0.626
.35	Silty	0.4637	0.014396	0.0009548	16.35	0.663
.40	Silty	0.4814	0.015563	0.0010656	17.63	0.699
.45	Silty Loam	0.4970	0.016671	0.0011733	18.90	0.733
.50	Silty Loam	0.5124	0.017740	0.0012777	20.15	0.767
.60	Silty Loam	0.5359	0.019730	0.0014768	22.60	0.830
.70	Silty Loam	0.5550	0.021591	0.0016652	24.98	0.889
.80	Sandy Loam	0.5718	0.023352	0.0018417	27.28	0.945
.90	Sandy Loam	0.5854	0.025004	0.0020096	29.51	0.999
1.00	Sandy Loam	0.5978	0.026596	0.0021679	31.68	1.050
1.50	Sandy	0.6412	0.033670	0.0028384	41.42	1.282
2.00	Sandy	0.6712	0.039805	0.0033508	49.38	1.483
4.00	Sandy	0.7490	0.059571	0.0044606	63.40	2.131

Figure II-8. The NRCS reference intake family for initial continuous flow furrow irrigations.

The root zone deficit, z_{req}, is entered in the input boxes below the **Tables** buttons. These values are always entered as the target <u>depth</u> of irrigation or the <u>depth</u> of the soil moisture deficit and can be converted to an equivalent volume per unit length as follows:

Root Zone Soil Moisture Depletion, zreq, inches

4.000	4.000	4.000	4.000

Required Intake Opportunity Time, min

204.302	737.536	259.928	415.699

$$Z_{req} = z_{req}w \tag{II-7}$$

in which w is the unit width in feet for borders and basin or the irrigated furrow spacing. For convenience the values of root zone moisture depletion in these input are entered in units of inches and then are converted into units of feet for use in the infiltration equations where k, f_o, and c values have units of ft, ft/min^a, and ft respectively for borders and ft^3/ft/min^a, ft^3/ft/min, and ft^3/ft for K, F_o, and C in furrow infiltration.

Below the input boxes for the root zone depletion are the associated intake opportunity times to achieve infiltration equal to the root zone deficit. In the figure above, a 4-inch deficit

will require 204 minutes of infiltration. These input boxes are updated whenever values of the intake coefficients or z_{req} are input. Values of intake opportunity time can also be input directly and the values of z_{req} will be adjusted automatically.

At the bottom of the page are four checkboxes to switch between English and metric units and between furrow and border/basin configurations. This feature is provided in the software to allow the user to compare the furrow and border/basin intake parameters for various unit widths, furrow geometries, and flow rates. The simulations can be run from this point if the user wishes to compare furrow and border irrigation performance (if the field has a slope) or level furrows and basin irrigation if the field is level.

Finally, at the right of the intake parameters are three input boxes and a button labeled **Two-Point**. The software uses what is called the two-point volume balance procedure to estimate the *a* and *k* or *K* intake parameters. A more detailed explanation of this procedure will be provided later in Section III.3.2. Usually, field measurements of advance time to the field midpoint and end are made to adjust intake parameters, thus this tool is part of the software's evaluation capability.

II.4.3 Inflow Controls

The **SURFACE** programming is controlled by the model control parameters as shown in Fig. II-9. User input is required for three options: (1) **Simulation Shutoff**; (2) **Inflow Regime**; and (3) **Run Parameters**.

Figure II-9. The Inflow Controls panel of the input tabbed notebook.

II.4.3.1   *Simulation Shutoff Control*

The basic "cutoff" or "shutoff" for surface irrigation system occurs when the inflow to the furrow, border or basin is terminated at the field inlet. Unlike drip or sprinkle systems in which this represents the end of the water applications, surface irrigation systems have a continuing or recession phase that can, depending on the type of system and its configuration, involve a significant application of water to parts of the field.
The termination of field inflow for the purposes of software
execution is defined by two check boxes and an input box, "Time of Cutoff". Under the heading **Simulation Shutoff Control**, the user must select either to terminate inflow at a specific time ("By Elapsed Time or Number of Surges") or when the downstream end of the field has received a depth of water approximately equal to z_{req}.

Time of Cutoff, mn   420.0

As a numerical safety measure, the "Time of Cutoff" will always terminate the simulated inflow even when the check box "By Target Application, zreq" is checked. Thus, to let inflow control to be managed by z_{req}, the cutoff time must be entered as a large value. Likewise, the number of surges specified for surged systems dominates the applied depth control and should be set to a large number. If z_{req} controls the shutoff time, the control value is the same as z_{req} specified in the **Infiltration Characteristics** panel. The simulation portions of the models also require a time step which is designated as "Dtm". The software always computes a default value which can be overridden with an input value, particularly if the
software is encountering convergence or stability problems in the
numerical procedure.

Dtm, mn   2.00

The discharge the program will use in the
simulation is specified by the user's entry into the
Simulated Unit Inflow box.

Simulated Unit Inflow, gpm   31.701

II.4.3.2   *Inflow Regime*

The **SURFACE** software will simulate both continuous and surge flow irrigation. There are three continuous and four surge flow regimes as shown in Fig. II-9. The user may select one regime at a time by clicking on the respective check box.

Generally, surface irrigation systems are designed with a fixed inflow during the advance phase. This value is specified in the **Simulated Unit Inflow** box. Note that this flow is the discharge into each furrow or into each unit width of border or basin. Occasionally, during efforts to evaluate surface irrigation systems, an inflow hydrograph is measured and the user would like to evaluate the effect of inflow variations. This option requires the **Continuous Inflow Hydrograph** check box to be selected and an input hydrograph specified in the **Hydrograph Inputs** panel in the tabbed notebook.

Under a surge flow regime, there are two cycle options. The first is a fixed cycle on-time surge flow system and the second is a variable on-cycle time option. It is assume that the off-time equals the on-time and thus the actual cycle time is double the on-time. In other words, the cycle ratio, on-time divided by cycle time is always 0.50.

SURFACE offers two ways to vary the surge to surge cycle on-time. The first is by multiplying the first surge on-time by a user-specified fraction (See the **Surge Adj. Ratio** edit box). For example, if the first surge on-time is 30 minutes and it is desirable to expand the surges by 10% each cycle, then the **Surge Adj. Ratio** can be set to 1.1. The second way of

varying the surge cycle time is by adding a fixed amount of time to each surge on-time via the **Surge Adj Time** parameter. If one begins with a 60 minute cycle and wishes to expand it by 10 minutes each surge, then the **Surge Adj Time** parameter is set to 10. In both cases of variable cycle surge flow, the cycle times can be compressed by specifying a value less than 1.0 for **Surge Adj. Ratio** or a negative number for **Surge Adj Time** the user should be careful with this input.

The concepts of continuous and surge flow are fairly standard surface irrigation terms. Cutback is a concept of having a high initial flow to complete the advance phase and a reduced flow thereafter. Both continuous and surged systems can operate with a cutback regime. If a cutback regime is selected, two additional parameters are required. The first is the definition of the **Cutback Ratio** and the second is the definition of **CB Length Fraction**. A cutback ratio of 0.80 results in a reduction of inflow to 80% of the initial flow. A cutback length fraction of 0.8 initiates the cutback flow when the advance has completed 80% of the field length. Likewise, a cutback length fraction of 1.2 results in the cutback when the software estimates the advance would have exceeded the field length by 20%. In surge flow simulation, the **CB Length Fraction** should always be set to a value greater than 1.0.

There is one note of caution. If the advance phase has been completed and the cutback is sufficient to dewater the end of the field, the simulations will often fail. These are situations where the cutback causes a front-end recession prior to inflow shut off. In some cases the simulations will compute the front end recession and subsequent advance without problems, but the numerical failures are common enough that the software has been programmed to discontinue simulation for all case of front-end recession during cutback.

II.4.3.3   *Leaching Fraction*

Although the software does not simulate or evaluate water quality parameters like salinity, the definition of irrigation efficiency includes a leaching fraction term. A more detailed discussion of efficiency is given in Section III.

II.4.3.4   *Simulation Speed and Graphical Presentation*

Modern computers will execute the most intensive of the *SURFACE* programming too fast for a clear run-time graphical presentation. In order to adjust computational speed, the software has built-in delays that can be adjusted by moving the **Simulation Speed** track bar to the right (faster) or left (slower).

The lower track bar will adjust the plotting slope of the run-time surface and subsurface profiles. This feature has been included solely for presentation purposes and has no computational or physical ramifications.

II.4.4 Hydrograph Inputs

Three of the important uses of software such as *SURFACE* are: (1) to evaluate the operation of existing surface irrigation systems; (2) to simulate the design of a surface irrigation system; and (3) to compare the simulated and measured conditions. The *Hydrograph Inputs* panel of the input tabbed notebook has been included to provide a convenient way to input three important field measurements, which might be useful in the three main uses of the software.

These three field measurements are: (1) an inflow hydrograph; (2) a tailwater or runoff hydrograph; and (3) advance and recession trajectories. On the panel are three mini-spreadsheets as shown in Fig. II-10. Data in these spreadsheets can be input from or output to Microsoft Excel spreadsheets with simple drag and drop or copy and paste operations.

| Inflow Controls | Field Topography/Geometry | Infiltration Characteristics | **Hydrograph Inputs** | Design Panel |

	A	**B**			**A**	**B**			**A**	**B**	**C**
1	Inflow Hydrograph			**1**	Tailwater Hydrograph			**1**	Advance and Recession		
	Elapse Time,	Inflow, gpm			Elapse Time,	Outflow, gpm			Distance From	Advance Time,	Recession Time, mn
2	mn			**2**	mn			**2**	Inlet, ft	mn	
3	.0	17.594		**2**	mn			**3**	.0	.0	26.0
4	6.0	17.594		**3**	206.0	1.427		**4**	82.0	3.1	705.0
5	20.0	16.484		**4**	220.0	2.695		**5**	164.0	6.9	-1.0
6	56.0	16.167		**5**	238.0	3.329		**6**	246.1	11.5	715.0
7	135.0	12.680		**6**	318.0	2.695		**7**	328.1	15.5	-1.0
8	145.0	12.680		**7**	495.0	3.963		**8**	410.1	20.5	717.7
9	202.0	12.522		**8**	550.0	3.963		**9**	492.1	25.1	-1.0
10	296.0	10.778		**9**	630.0	4.121		**10**	574.1	29.0	723.5
11	360.0	11.254		**10**	650.0	4.280		**11**	656.2	33.5	-1.0
12	550.0	12.046		**11**	.0	.000		**12**	738.2	38.5	726.5
13	705.0	.000		**12**	.0	.000		**13**	820.2	44.2	-1.0
14	.0	.000		**13**	.0	.000		**14**	902.2	50.0	728.0
15	.0	.000		**14**	.0	.000		**15**	984.2	56.3	-1.0
16	.0	.000		**15**	.0	.000		**16**	1066.3	-1.0	733.3
17	.0	.000		**16**	.0	.000		**17**	1148.3	69.5	-1.0
18	.0	.000		**17**	.0	.000		**18**	1230.3	77.2	735.5
19	.0	.000		**18**	.0	.000		**19**	1312.3	85.5	-1.0
20	.0	.000		**19**	.0	.000		**20**	1394.3	92.7	741.0
21	.0	.000		**20**	.0	.000		**21**	1476.4	101.1	-1.0
22	.0	.000		**21**	.0	.000		**22**	1558.4	110.3	746.0
23	.0	.000		**22**	.0	.000		**23**	1640.4	118.7	-1.0
24	.0	.000		**23**	.0	.000		**24**	1722.4	131.3	751.5

| Update Inflow Hydrograph | Update Outflow Hydrograph | Update Advance/Recession Data |

Figure II-10. The Hydrograph Input panel of the input tabbed notebook.

The first mini-spreadsheet describes the inflow hydrograph. These data can be measured in the field or simply input by the user to test a flow change behavior of the system. The hydrograph is defined by elapsed time (the time since the beginning of irrigation), and the discharge into a furrow or border/basin unit width. It is not necessary to develop and input these data on equal time steps as the software includes interpolation algorithms to match computational points with the input points.

The second hydrograph is for any surface runoff of tailwater that might be recorded or estimated. It is not necessary to have a tailwater hydrograph if, for example, the end of the field is blocked.

Finally, a mini-spreadsheet is available to record advance and recession trajectories. In this case, the data do not represent a hydrograph and may have points on the two trajectories where data are not available. If data are not available for both trajectories or at certain points, the user should enter a -1 as shown. The software will ignore the negative values and use what data points are available to plot the trajectories.

Below the spreadsheets are three buttons labeled "**Update Inflow Hydrograph**". Clicking on each of these buttons is necessary to record the data in the software arrays for use and storage later. Any input data not updated with these buttons will not be available to the computational algorithms of the software nor for later storage in files. However, once updated, the hydrographs and trajectories are stored in the *cfg* file and will reappear upon opening such a file. It is not necessary to update these data once recorded unless changes are made. And, it

should be noted that any updated data in these spreadsheets will be plotted in the graphic output screens discussed below whenever the **Continuous Inflow Hydrograph** check box is checked.

II.4.5 Design Panel

The interactive design capabilities of the *SURFACE* software will be discussed in a separate section below. It has been included with the input tabbed notebook to facilitate data entry and change during the interactive design process.

II.5   OUTPUT

The *SURFACE* software includes both tabular and graphical display output capabilities. Output is accessed from the main screen by selecting *Output* and then choosing either printed or plotted output from the drop-down menu. Printed output can be accessed directly by clicking once on the ⊞ button, and likewise, plotted output can be directly accessed by the ⊠ button.
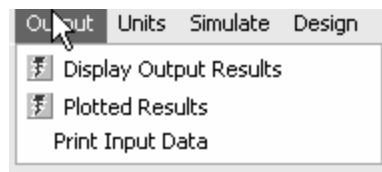
If the user would like a printout of the software's basic input data, then the "Print Input Data" option can be selected.

II.5.1   Printed Output

Figure II-4 showed the primary printed output screen. Selecting the *File* option from the main command bar provides various print and save options. Data can be saved in a comma delimited text file, but the mini-spreadsheets on the form are also Microsoft Excel compatible so the user can also drag and drop or copy and paste the data from the screen directly. Tabular output can be either printed or previewed. Each selection of the print or save options allows the user to choose one of two sets of data: (1) the advance/recession/infiltration profiles; and/or (2) the runoff hydrographs.
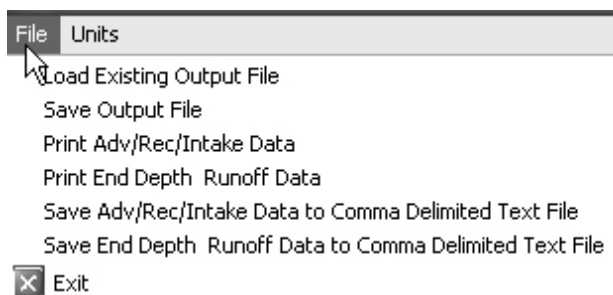
A *Units* option on the main command bar is available to change the units of previewed or printed data.

II.5.2   Plotted Output

Choosing plotted output reveals the plotting screen. The screen command bar has two drop-down menus accessed by selecting *Files* or *Current Data Plot Options.* The *Files* options are either to open and existing output file or to save the current output to a file, either of which lead to standard file open/save dialog boxes.

The *Current Data Plot Options* selection provides plots of advance and recession, a runoff or tailwater hydrograph, depth of water at the end of the field, and the distribution of applied depths
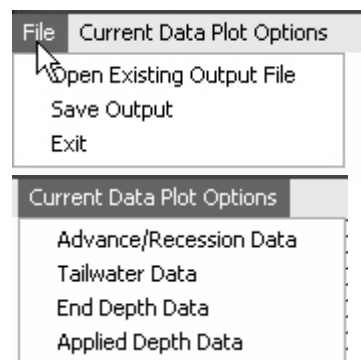
over the field. A typical plot of the advance recession data is shown in Fig. II-11 showing as well data from recorded field measurements. Figure II-12 shows a typical tailwater hydrograph and Fig. II-13 shows the plot of infiltrated water.
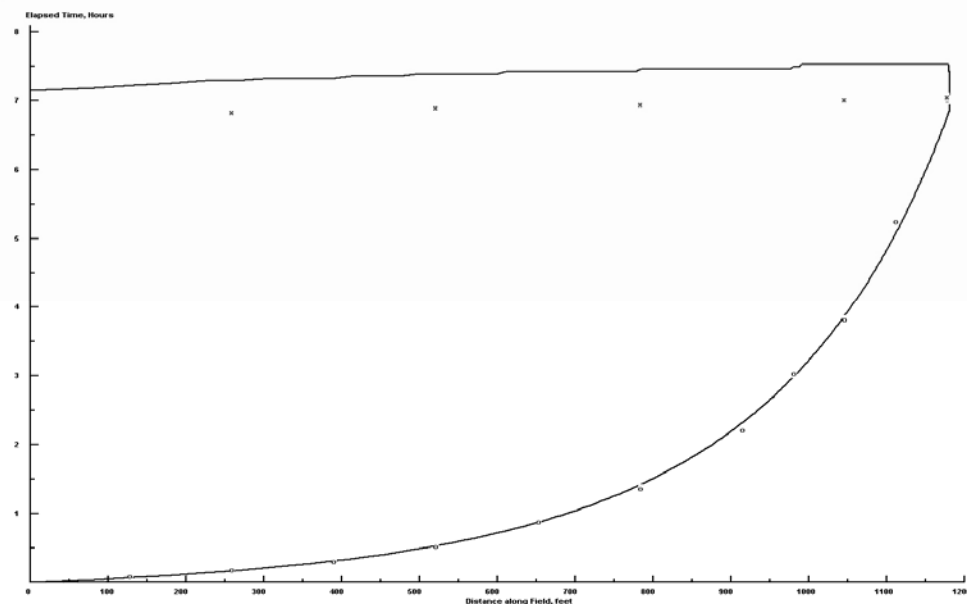
Figure II-11. A typical advance/recession plot from the *SURFACE* graphics output.
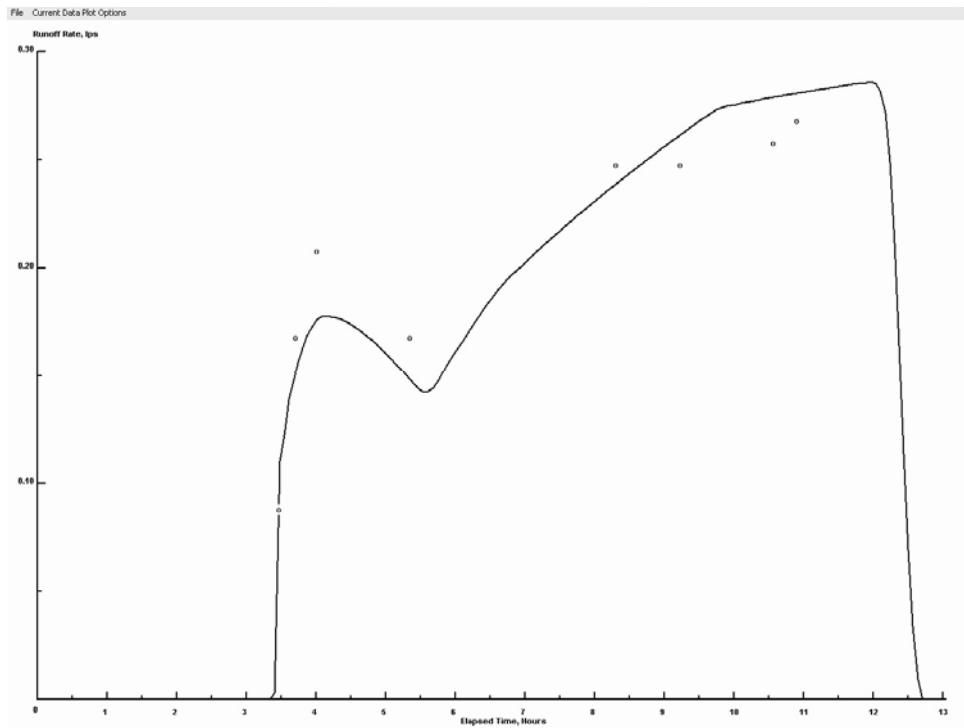
Figure II-12. A typical runoff hydrograph from the *SURFACE* graphic output.
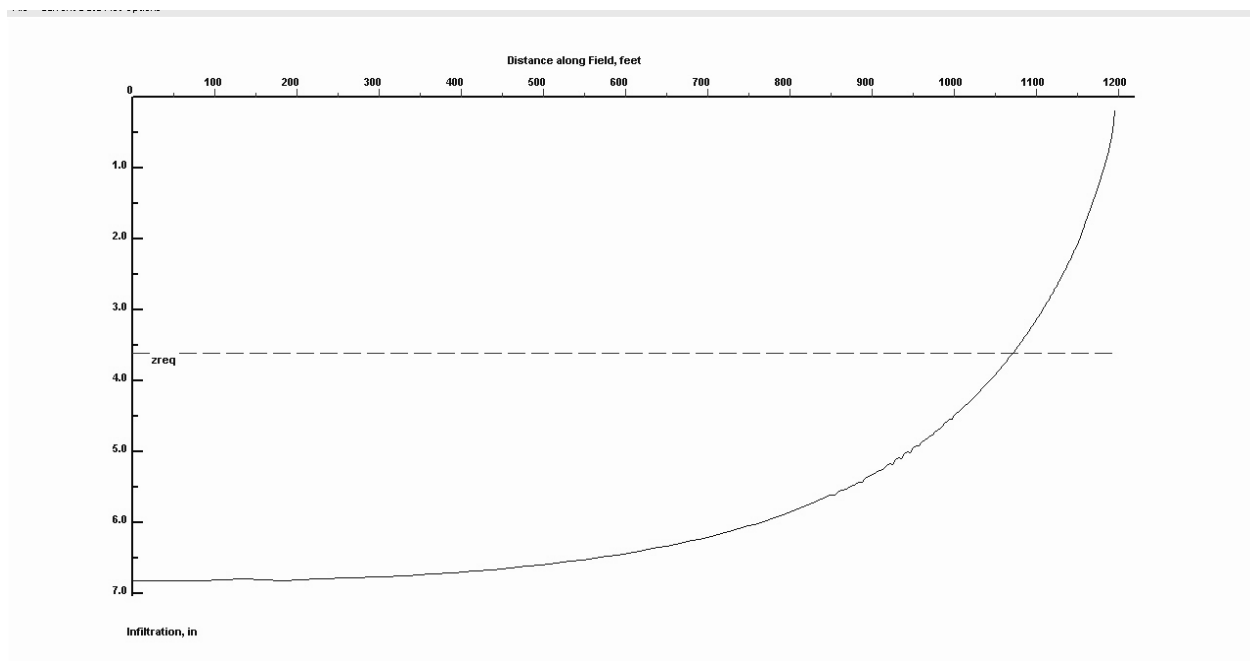
Figure II-13. A typical plot of intake distribution for the *SURFACE* graphics output.

II.6 SIMULATION

Once the input and control data have been entered, the simulation is executed by clicking on the calculator button ▣ or the simulate menu. The simulation screen will appear and the run-time plot of the advance and recession profiles will be shown as illustrated in Fig. II-14.
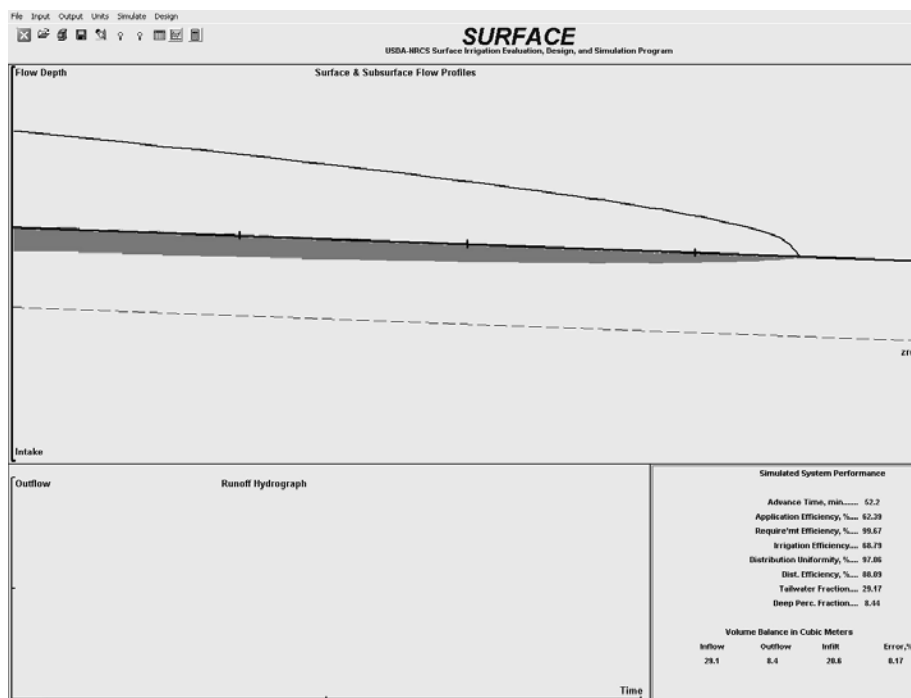
Figure II-14. The main simulation screen.

There are three important regions in the simulation screen. The first occupies the upper

two-thirds of the screen and plots the surface and subsurface movements of water as the advance and recession trajectories are computed. The target or required depth of application is plotted as z_{req} so that when an infiltrated depth exceeds this value the user can see the loss of irrigation water to deep percolation (The subsurface profile color changes as the depth exceeds z_{req}).

In the lower right side of the screen a summary of the simulated irrigation event will be published after the completion of recession. The uniformity and efficiency terms are defined later in Section III. The bottom four edit windows give a mass balance of the simulation, including an error term describing the computed differences between inflow, infiltration, and runoff (if the field is not diked). As a rule an error less than 5% is acceptable – most simulations will have errors of about 1%.

In the lower left side of the screen, a runoff hydrograph will be plotted for the cases where the downstream end of the field is not diked.

Note that neither the advance-recession nor the runoff hydrograph are intended to be quantitative, as no units are included in the plot. These details are presented in the plotted and printed output from the model.
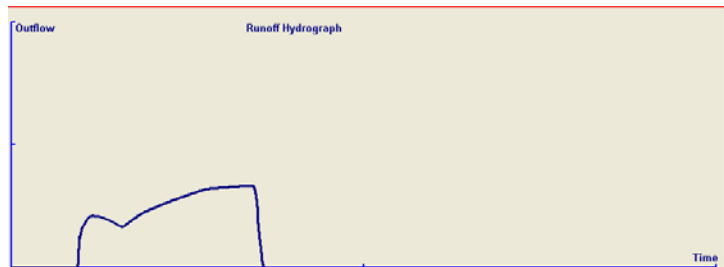
II.7   DESIGN

The **SURFACE** software includes an interactive field design program located within the input data tabbed notebook. This panel is shown in Fig. II.15.

Figure II-15. The *SURFACE* design panel.

II.7.1 Input Data for Design

Although the interactive design process does not require all of the data needed for the respective input tables, it is prudent to enter all of the information for the input tabbed notebook table, **Inflow Controls**; **Field Topography/Geometry**; and **Infiltration Characteristics**. The hydrograph inputs are not required because designs are based on a fixed inflow rate. There are then five special inputs for the design process: (1) total available flow; (2) total time flow is available; (3) maximum non-erosive flow velocity; (4) the design flow per unit width; and (5) the design cutoff time. Note that the design flow per unit width and the cutoff time may be different than the "Simulated Unit Inflow" and the "Time of Cutoff" entered into the *Inflow Controls* table. Thus, if the calculator button, ▣, is selected on the main window command bar, the simulation will be different than if the "**Simulate Design**" $\boxed{\textit{Simulate Design}}$ button in the design panel is selected. The flow, time of cutoff, and run length can be different.

II.7.1.1 Total Available Flow

The field water supply is defined by its discharge, duration, and frequency of availability. For design purposes, the total available flow entry on the design panel should be the maximum available to the field. This should be a relatively reliable maximum since the field configuration will depend on this flow for efficient operations.

In many cases of surface irrigation the available flow from the delivery system will not efficiently irrigate the entire field at one time, or with one "set". Consequently, the field must be partitioned into "sets" which are irrigated sequentially. The number of sets depends on the total available flow as follows:

$$N_s = \frac{Q_o W_f}{Q_T w} \frac{L}{R_L} \tag{II-8}$$

where N_s is the number of sets required to irrigate the field; W_f is the width of the field; w is the unit width in the same units as W_f; Q_T is the total available flow; Q_o is the design flow in the same units as Q_T; L is the length of the field; and R_L is the run length in the same units as L. As an example, suppose the field is 2361 feet in width and should be irrigated by furrows spaced at 3 foot intervals and with a unit flow of 24 gpm. The field is 1180 feet long but will be subdivided into 590 foot long furrows. If the available flow to the field is 2376 gpm, the number of sets will be:

$$N_s = \frac{24\ gpm \cdot 2361\ feet}{2376\ gpm \cdot 3\ feet} \frac{1180\ feet}{590\ feet} = 16$$

II.7.1.2 Total Time Flow is Available

Depending upon the policies of the delivery system, there may be a limit on the time the flow will be made available to the field. For instance, many systems operate on a rotational delivery scheme where the field can receive water every 7-21 days for a fixed number of hours. Suppose the "set time" or the time required by each set to completely irrigate it is 4 hours or 240 minutes. The time needed to irrigate the entire field is:

$$T_T = N_s \cdot t_{co} = 16\ sets \cdot 4\ hrs\ /\ set\ =\ 64\ hours$$

in which T_T is the total required time and t_{co} is the cutoff time for each set.

The required total time to irrigate the field has to be less than the actual total time the flow is available, or else, the field must be irrigated at different times.

II.7.1.3   Maximum Velocity

In order to prevent erosion, the designer will need to place an upper limit on flow velocity over the field. This limit may be as low as 30 ft/mn for erosive soils to as high as 75 ft/mn if the soil is quite stable. The actual velocity over the field will be highest at the field inlet and will depend on the unit discharge, field slope, and field roughness.

Generally, erosive velocity is more of a concern in furrow irrigation than in border irrigation. It is generally not a concern in basin irrigation except near the delivery outlets. Typical values of maximum velocity for furrow systems are shown in the following table.

Soil Type	Suggested Maximum Non-Erosive Velocity in feet/min
Fine sands	30
Sandy Loams	36
Silt Loams	39
Clay Loams	49
Clay	75

II.7.1.4   Design Flow

The performance of surface irrigation systems is highly dependent on the unit discharge and thus this parameter may be the most important management parameter either the designer or irrigator considers. Unit flows that are too small advance slowly and can result in poor uniformity and efficiency as well as excessive deep percolation. Flows that are too high may result in low efficiencies due to excessive tailwater or downstream ponding although the uniformities will typically be high.

In an interactive design process, the designer searches for a design flow that maximizes efficiency subject to a lower limit on adequacy. For example, one may wish to find the flow that maximizes irrigation or application efficiency while insuring that at least 95% of the field root zone deficit has been replaced by the irrigation.

II.7.1.5   Cutoff Time

Shutting the flow off when irrigation is complete is one of the most important operational parameters in surface irrigation and one that is often most difficult to determine. Many irrigators choose "convenient" cutoff times, also called "set times", in order to reduce irrigating time or move the delivery from set to set at easily scheduled times.

As a rule, designed cutoff times should be an integer fraction of a day and hourly. For instance, one could have 1, 2, 3, 4, 6, 8, and 12 hours set times in one day. Setting a cutoff time of 252 minutes is unworkable without automation. Having said this however, under severe water supply constraints, many irrigators manage their water on intervals that are highly variable and often at intervals of much less than an hour.

II.7.2 Field Layout

On the right side of the design panel the **SURFACE** software includes a field divider tool. Two up-down buttons are provided at the top of a rectangular representation of the field. Note the width and length scales are not equal so that very wide fields still assume the vertical rectangular shape.

By clicking on the top or bottom button of the vertical up-down button the field can be subdivided along its length axis. As shown, the field length has been cut in half. Likewise, by clicking on the buttons of the horizontal up-down button, the field width can be subdivided. In this case the field has been subdivided into 4 width sections. Each rectangular subdivision represents one "set" in the irrigation scheme – in the case here there are 8 sets.
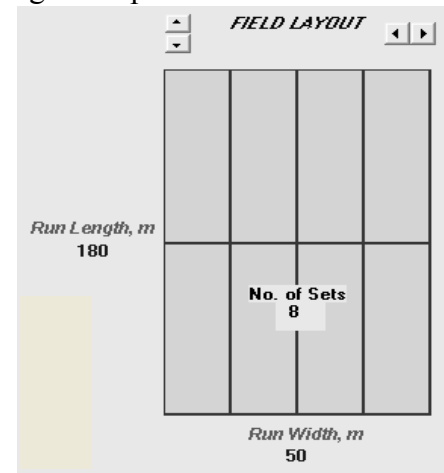
The easiest way to interactively design a surface irrigate field with the **SURFACE** software is to determine the most efficient unit discharge and then subdivide the field until the constraints on total available supply and total available time are satisfied. This will be demonstrated in a following section.

In many situations the fields that require re-design have irregular shapes. It may be necessary to partition the field into two or more separately managed units to achieve a square or rectangular layout. In other cases it may be necessary to design for a single field dimension like the average run length, or a set of average run lengths corresponding to the dimensions of the expected set layout. It is always good practice to evaluate the extreme conditions like the maximum and minimum run lengths to anticipate the management problems the irrigator will face.

II.7.3 Simulation of Design

The interactivity of the **SURFACE** design programming is accessed by clicking on the "**Simulate Design**" button at the bottom of the design panel. The run-time advance, recession, tailwater hydrograph, and results will shown on the main screen. The results will also be posted on the design panel as noted below. During the design simulation, the input tabbed notebook will be hidden until the simulation is completed. If the simulation is interrupted, the user will need to click on the button to make the tabbed notebook re-appear. Iteratively choosing the design flow, cutoff time, and then if necessary the run length will allow the user to develop designs that produce maximum efficiencies and uniformities.
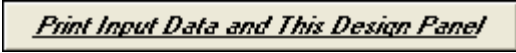
II.7.4 Results

Each design simulation produces an estimate of its performance with six indicators:

Results	
Application Efficiency, %	75.18
Irrigation Efficiency, %	81.61
Requirement Efficiency, %	99.14
Distribution Uniformity, %	95.05
Tailwater Fracton, %	16.43
Deep Percolation Fracton, %	8.38

1. Application Efficiency – the percentage of the field delivery that was captured in the root zone of the crop;

2. Irrigation Efficiency – an extension of Application Efficiency to include leaching water where a leaching fraction has been specified;

3. Requirement Efficiency – the percentage of the root zone deficit that is replaced during the irrigation;

4. Distribution Uniformity – the ratio of applied water in the least watered 25% of the field to the average over the entire field;

5. Tailwater Fraction – the fraction of applied irrigation water that runs off as tailwater; and

6. Deep Percolation Fraction – the fraction of applied water percolating below the root zone.

II.7.5 Printed Output

A printout of the principle input data and a graphical print of the design panel can be obtained by clicking the **Print Input Data and This Design Panel** button. The graphical printout of the design panel will be the same as illustrated in Fig. II-16 and will require a graphics-capable printer.

II.8   SAMPLE DATA SETS

II.8.1 FreeDrainingFurrow_1.cfg

The FreeDrainingFurrow_1 data set describes a 64 acre furrow irrigated field supplied by a well with a capacity of 2400 gpm. The furrows are irrigated on 30-inch spacings. The soil is a silt loam with an average 6-hr intake rate of 0.2585 ft^3/ft/hr which within the 2.5 foot furrow spacing, is 1.24 in/hr (Curve No. 1.00- 1.50). The target depth of application is 4-inches. The furrow stream is 32 gpm with a 8-hour cutoff time. The maximum non-erosive velocity of 39 feet/min was taken from the table shown earlier.

A simulation of these data reveals that substantial over-irrigation occurs at the upper end of the field and substantial under-irrigation occurs at the downstream end. The application efficiency is about 48%, primarily because more than 51% of the inflow was lost in deep percolation. For a 4-inch irrigation it would require only 160 minutes to infiltrate the desired depth. The 8-hour cutoff time is necessary to allow completion of the advance time.

II.8.2 FreeDrainingFurrow_2.cfg

The FreeDrainingFurrow_2 data describe a 113 acre field supplied by a canal. The typical canal flow that is available to the field is 10.0 cfs. The field is currently irrigated by furrows on 30 inch spacings with a required depth of application of 3.5 inches. The soil is a clay

loam with an average 6-hr intake rate of 0.052 ft^3/ft/hr or 0.25 in/hr (Curve No. 0.25) over the 2.5 foot spacing of the furrows. An inflow of 0.033 cfs is being applied over a 24-hour set time. The maximum non-erosive velocity was assumed to be 49 ft/min.

The uniformity of this irrigation is excellent at nearly 97% but the application efficiency is poor at only 52% primarily because nearly 40% of the applied water is lost as tailwater. There is about 7.5 percent deep percolation which is excessive given the leaching fraction of 5%.

II.8.3 FreeDrainingBorder_3.cfg

This data set describes a 33 acre field supplied by a well with a capacity of 3400 gpm. The soil is a clay but with an average 6-hr intake rate of 0.54 in/hr in part because of a cracking component.

The field is currently irrigated as a free draining border using 1200 foot runs and a unit flow of 13.5 gpm/ft. The inflow is cutoff at 4 hours and before the end of the advance phase. The resulting application efficiency is 69%. The field requires a leaching requirement of 9% but this irrigation configuration produces a 20% deep percolation. In addition, more than 11% of the inflow resulted in tailwater.

This field has a grass surface which is described by a Manning n value of 0.18 during both initial and later irrigations.

II.8.4 FreeDrainingBorder_4.cfg

The FreeDrainingBorder_4 data describe a 24.7 acre field irrigated by canal water supply having a maximum flow rate of 6 cfs and a maximum availability of 48 hours. The soil intake characteristics were selected on the basis of NRCS curve 0.50 which has an average 6-hour intake rate of 0.5 in/hr.

Based on the simulation of this field using the NRCS 0.50 intake curve, a unit flow of 0.036 cfs/ft applied for 4 hours, the application efficiency of this system would be about 39% due primarily to a loss of almost 44% of the inflow to tailwater. A 10% leaching requirement was more than satisfied with the nearly 17% of deep percolation.

II.8.5 BlockedEndBorder.cfg

This data set describes a border irrigated field of 33 acres having 1,200 foot dimensions. It has a relatively steep slope of 0.00264 but also relatively rough surface indicated by a Manning n of 0.24 for initial and later irrigations due to a crop like alfalfa growing in the border.

The six-hour intake rate for this soil is 0.55 in/hr. The target application depth is 3 inches and with the intake coefficients given will require an intake opportunity time of about 312 minutes for initial irrigations and 441 minutes for later irrigations.

With a unit flow of 0.025 cfs/ft the field irrigates with an application efficiency of 66%. The 5% leaching fraction is exceeded by a deep percolation of about 33%.

II.8.6 Basin_5.cfg

The Basin_5 data comes from a 19.7 acre field irrigated by a canal water supply limited to 5.3 cfs over a 48 hour period. The soil has a 6-hour intake rate of 0.95 inches/hour which is typical of silt loam soil. The target depth of application is 4 inches.

A simulation of the data as given shows an application efficiency of about 57% due primarily to a deep percolation loss of about 43%. The flow barely completes the advance phase in the 7 hours of application so there is also substantial under-irrigation near the downstream end of the basin.

II.8.7 Basin_6.cfg

The Basin_6 data comes from a large 193 acre basin system with a clay soil (the average 6-hour intake rate is 0.47 in/hr). An irrigation district supplies water to the field with an upper limit on flow of 16 cfs and availability of 96 hours per irrigation.

Under present operations, the application efficiency is about 63%. A 5% leaching requirement is exceeded by a deep percolation loss of more than 36% of the inflow.

II.8.8 CutbackDesign.cfg

A furrow irrigated field of about 21 acres is supplied by a well with a capacity of 1200 gpm. Each furrow is initially irrigated with a flow of 14 gpm which is reduced to 8.4 gpm after the advance phase is completed. The total set time is 12 hours and the resulting application efficiency is more than 79%. If the cutback is not initiated the application efficiency would decrease to 51% as the tailwater losses increase from 21% to about 49% of the total inflows.

The soil of this field is a clay loam with an average 6-hour infiltration rate of 0. ft^3/ft/hr or 0.24 in/hr (Curve No. 0.25) over the 2.5 foot spacing of the furrows. The target applied depth is 2.5 inches which is not quite satisfied. There is also a 5% leaching to consider.

III Surface Irrigation Evaluation

III.1 INTRODUCTION

An evaluation of a surface irrigation system will identify various management practices and field layouts that can be implemented to improve the irrigation efficiency and/or uniformity. The evaluation may show, for example, that achieving better performance requires a reduction in the flow and duration of flow at the field inlet, or it may indicate that improvements require changes in the field size and topography. Perhaps a combination of several improvements will be necessary.   Thus, the most important objective of the evaluation is to improve surface irrigation performance. The procedures for field evaluation of irrigation systems are found in the NRCS National Engineering Handbook Part 652, National Irrigation Guide, particularly Chapter 9 – "Irrigation Water Management." This section will not attempt to repeat each of the various procedures applicable to surface irrigation but to supplement some of them in more detail or with more recent developments.

III.2 SOME IMPORTANT SURFACE IRRIGATION CONCEPTS

III.2.1 Soil Moisture

As commonly defined, the available moisture for plant use is the soil water held in the soil matrix between a negative apparent pressure of one-tenth to one-third bar (field capacity) and a negative 15 bars (permanent wilting point). However, the soil moisture content within this pressure range will vary from 3 inches per foot for some silty loams to as low as 0.75 inches per foot for some sandy soils.

Consider the simplified unit volume of soil comprised of solids (soil particles), liquid (water), and gas (air) as shown in Fig. III-1. The porosity, (ϕ), of the unit volume is

$$\varphi = \frac{V_p}{V} \tag{III.1}$$

The volumetric water content, θ, is

$$\theta = \frac{V_w}{V} \tag{III-2}$$

The saturation, S, which is the portion of the pore space filled with water, is

$$S = \frac{V_w}{V_p} \tag{III.3}$$

Porosity, saturation, and moisture content in a soil are related by the expression:

$$\theta = S\varphi \tag{III-4}$$

There are a number of ways to measure water in a soil. These include: tensiometers; resistance blocks; wetting-front detectors; soil dielectric sensors; time domain reflectometry; frequency domain reflectometry; neutron moderation; and heat dissipation[3]. However, one of the

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[3] Charlesworth, P. 2000. Soil Water Monitoring. Irrigation Insights Number 1. Land and Water Australia, GPO Box 2182, Canberra ACT 2601, Australia. 96 p. Email: <public@iwa.gov.au>

most common and simplest is the gravimetric method in which soil samples are extracted from the soil profile, oven-dried, and evaluated on the basis of the dry weight moisture fraction, W, of the soil sample:

$$W = \frac{\text{sample wet wt. - sample dry wt.}}{\text{sample dry wt.}} = \frac{W_w}{W_s} \tag{III-5}$$

V = Soil Volume
V_g = Volume of air
V_w = Volume of water
V_s = Volume of Soil Particles
V_p = Volume of Soil Pores
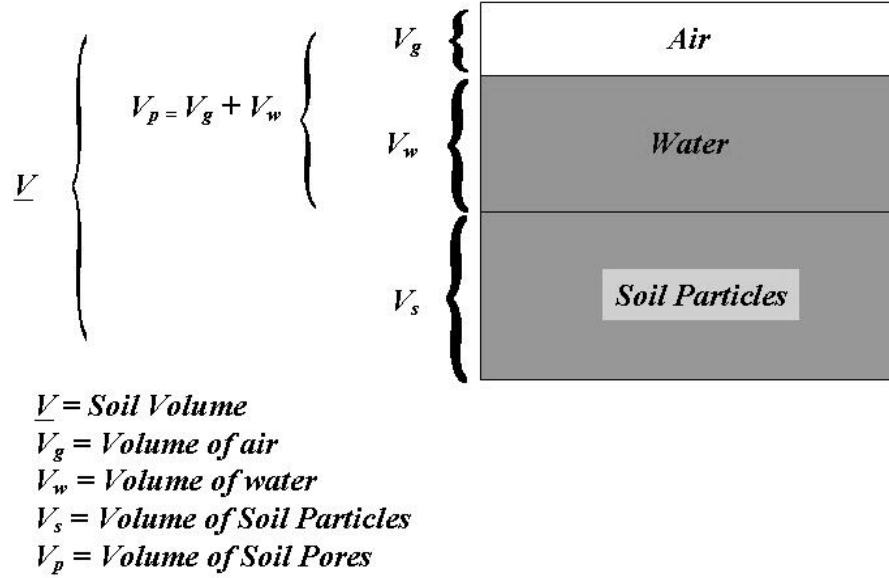
Figure III-1. Components of the soil-water matrix.

The dry weight moisture fraction can be converted to volumetric water content as follows:

$$\theta = \gamma_b W \tag{III-6}$$

where γ_b is the bulk density or bulk specific weight of the dry soil. Also, γ_b is related to the specific weight of the soil particles, γ_s, by:

$$\gamma_b = \gamma_s (1 - \varphi) \tag{III-7}$$

Field capacity, W_{fc}, is defined as the moisture fraction of the soil when rapid drainage has essentially ceased and any further drainage occurs at a very slow rate. For a soil that has just been fully irrigated, rapid drainage will generally cease approximately after one day for a "light" sandy soil and after approximately 3 days for a "heavy" soil. This corresponds to a soil moisture tension of 1/10 to 1/3 atm (bar).

The permanent wilting point, W_{pw}, is defined as the soil moisture fraction at which permanent wilting of the plant leaf has occurred and applying additional water will not relieve the wilted condition. This point is usually taken as the soil moisture content corresponding to a soil moisture tension of 15 bars.

The volumetric moisture contents at field capacity and permanent wilting point become:

$$\theta_{fc} = \gamma_b W_{fc} \tag{III-8}$$

$$\theta_{wp} = \gamma_b W_{wp} \tag{III-9}$$

The total available water, **TAW**, to the plants is approximately the difference in these volumetric moisture contents multiplied by the depth of the root zone, **RD**:

$$TAW = \left(\theta_{fc} - \theta_{wp}\right) RD \tag{III-10}$$

It should be noted that Eq. III-10 is not technically exact because crop roots do not extract water uniformly from the soil profile.

The relation among field capacity, permanent wilting point, total available water, and soil type is illustrated in Figs. III-2 and III-3. Table III.1 lists some common rooting depths for selected crops.[4]
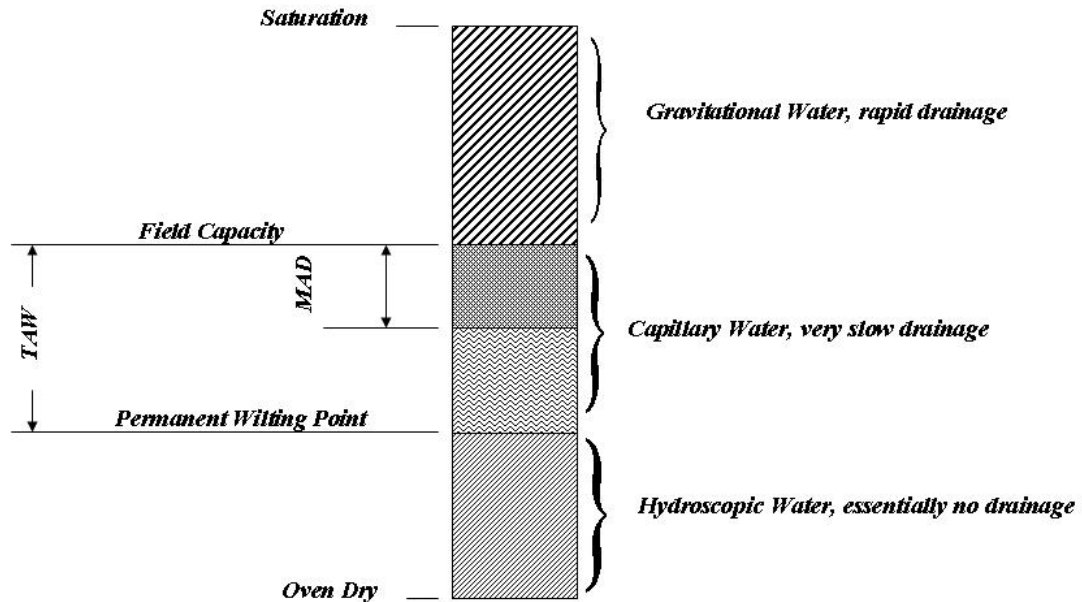
Figure III-2. Components of soil water.

[4] Doorenbos, J., and W. O. Pruitt. 1977. Crop Water Requirements (Revised Edition). FAO Irrig. Drain. Pap. 24. United Nations, Food and Agriculture Organization, Rome.
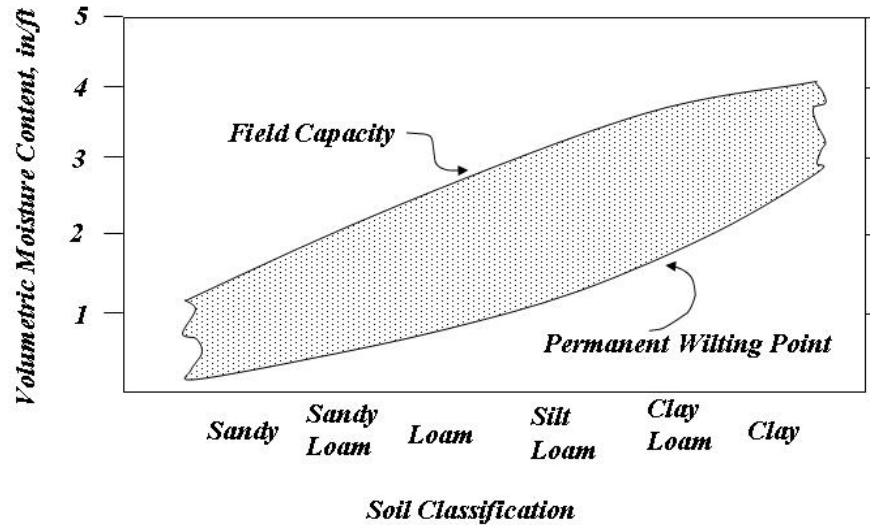
Figure III-3. Variation of available soil moisture with soil type.

TABLE III-1. AVERAGE ROOTING DEPTHS OF SELECTED CROPS IN DEEP, WELL-DRAINED SOILS.

Crop	Root Depth, ft	Crop	Root Depth, ft
Alfalfa	5	Grapes	3
Almonds	7	Ladino clover and grass mix	2
Apricots	7	Lettuce	1
Artichokes	4.5	Melons	5
Asparagus	3.0	Milo	4
Barley	4	Mustard	3.5
Beans (dry)	3.5	Olives	5
Beans (green)	3	Onions	1
Beans (lima)	3.5	Parsnips	3.5
Beets (sugar)	3	Peaches	7
Beets (table)	3	Pears	7
Broccoli	2	Peas	3
Cabbage	2	Peppers	3
Cantaloupes	5	Potatoes (Irish)	3
Carrots	2	Potatoes (sweet)	4.5
Cauliflower	2	Prunes	6
Celery	2	Pumpkins	6
Chard	3	Radishes	2
Cherries	4.5	Spinach	2
Citrus	4.5	Squash (summer)	3
Corn (field)	4	Strawberries	5
Corn (sweet)	3	Sudan grass	5
Cotton	4	Tomatoes	3
Cucumber	4	Turnips	3
Eggplant	3	Walnuts	7
Figs	7	Watermelon	5
Grain and Flax	4		

The management allowed deficit, *MAD*, is the soil moisture that can be used by the crop before irrigation should be scheduled. For deeply rooted and stress tolerant crops like alfalfa, the

MAD can be as much as 60-65% of **TAW** whereas for shallow rooted and stress sensitive crops like vegetables, the **MAD** level should not exceed 35-40% of **TAW**. Some crops like cotton and alfalfa seed require a stress period in order to produce lint or seeds and **MAD** may need to be as much as 80% of **TAW** for some irrigations late in the maturation period. In the absence of crop-specific information in a locality, assuming a **MAD** level of 50% of **TAW** can be generally used to schedule irrigations.

The soil moisture deficit, **SMD**, is the depletion of soil moisture at particular soil moisture content, θ, and can be expressed as a depth of water as follows:

$$SMD = \left(\theta_{fc} - \theta \right) RD \qquad\qquad \text{(III-11)}$$

III.2.1.1   Example 1

One of the most important characteristics of soil is its bulk density or bulk specific weight. When evaluating soil moisture, particularly with the gravimetric method, this parameter is necessary to accurately estimate **TAW, SMD, MAD**, etc. The following example is given to demonstrate these relationships.

What is the bulk density or bulk specific weight of an undisturbed sample 12 inches long by 1 inch in diameter and weighing when collected 0.573 lbs? The entire sample was oven-dried to specification and then saturated with 3.594 cubic inches of water. The specific weight of the soil particles is 165.434 lbs/ft³.

The solution to this question is found in Eq. III-7 which relates porosity to bulk density and the specific weight of the soil particles: Recognizing that the 3.594 in³ of water occupies the entire pore space in the sample then the porosity from Eq. III-1 is:

$$\varphi = \frac{V_p}{V} = \frac{3.594}{12 \cdot \dfrac{\pi (1)^2}{4}} = 0.381 = 38.1\%$$

Then from Eq. III-7 for γ_b yields:

$$\gamma_b = \gamma_s \left(1 - \varphi \right) = 165.434 \frac{lbs}{ft^3} \times \left(1 - 0.381 \right) = 102.404 \frac{lbs}{ft^3} = 1.640 \frac{gm}{cm^3}$$

III.2.1.2   Example 2

The most important uses of soil moisture characterizations are those that assist the irrigator determine when to irrigate and how much to apply. A corollary problem for the surface irrigation evaluation is determining the soil moisture prior to irrigation so an estimate of efficiency can be made. This example is a typical exercise as part of a surface irrigation evaluation.

A number of soil samples from throughout a 65 acre border-irrigated field were collected and evaluated gravimetrically. The bulk density, field capacity and wilting point were estimated for each soil depth during earlier evaluations. All the data were averaged by depth and are presented along with the average dry weight soil moisture fraction in the table below. How much water should the surface irrigation system apply based on these data?

Soil Depth, in	Soil Bulk Density, gm / cm³	W_{fc}	W_{wp}	W
0-6	1.25	0.24	0.13	0.16
6-12	1.30	0.28	0.14	0.18
12-24	1.35	0.31	0.15	0.23
24-36	1.40	0.33	0.15	0.26
36-48	1.40	0.31	0.14	0.28

The data presented above are presented on a dry weight basis not a volumetric basis and need to be converted as follows:

Soil Depth, D, in	$\theta_{fc} = \gamma_b W_{fc}$	$\theta_{wp} = \gamma_b W_{wp}$	$\theta = \gamma_b W$	Soil Moisture, in
0-6	0.300	0.163	0.200	1.200
6-12	0.364	0.182	0.234	1.404
12-24	0.419	0.203	0.311	3.732
24-36	0.462	0.210	0.364	4.368
36-48	0.434	0.196	0.392	4.704
Depth Weighted Average	0.412	0.195	0.321	

Values for two key soil moisture parameters that can be determined from the above data are as follows: (1) **TAW** = (0.412-0.195)(48 inches) = 10.416 inches; (2) **SMD**=(0.412-0.321)(48 inches) = 4.368 inches, or 41.9% of **TAW**. If the irrigation were to occur at this point, the volume the system should apply is 4.368 inches and this will require (4.368 in/12 in/ft)(65 ac) = 23.66 acre-feet.

If the reader works through this example one will note that expressing bulk density in gm/cm³ makes θ a dimensionless number since 1 gm of water has a volume of 1 cm³. This allows the evaluator to express the equivalent depth in any units desired.

III.2.2 Infiltration

III.2.2.1   Basic Theory
Infiltration is perhaps the most crucial factor affecting surface irrigation. This parameter controls the amount of water entering the soil and secondarily impacts the duration of both advance and recession. In other terms, infiltration has an important impact on the duration of the irrigation itself. Unfortunately infiltration exhibits very large variability over a field and is

difficult to characterize on a field scale because of the large number of measurements generally necessary.

One of the simplest and most common expressions for infiltration is the Kostiakov Equation which can be written in general terms for furrow irrigation as:

$$Z = K\tau^a \tag{III-12}$$

in which Z is the cumulative volume of infiltration per unit length, ft³/ft. The coefficient K has units of ft³/ft/minᵃ while a is dimensionless. The "intake opportunity time, ft, τ, has units of minutes.

In a border or basin where a unit width can also be defined, infiltration is expressed as:

$$z = k\tau^a \tag{III-13}$$

where z is the cumulative depth of infiltration, ft; the coefficient k has units of /ft/minᵃ and a is dimensionless as before. The units of Eqs. III-12 and III-13 must be different since a unit width such as that used for borders and basins cannot be used for furrow systems. The wetted perimeter of the furrow does not usually equal the distance between furrows.

The duration of the water application for border and basin systems is usually short enough that the intake rate derived from Eq. III-13, $I=\partial z/\partial\tau$, will not significantly underestimate infiltration at the end of irrigation. However it generally will in furrow irrigation systems. A more generally applicable relation for furrows is Kostiakov-Lewis Equation which adds a term for final or "basic" intake rate, f_o ft/min, for borders and basins, or F_o ft³/ft/min for furrows. The Kostiakov-Lewis function for furrows is:

$$Z = K\tau^a + F_o\tau \tag{III-14}$$

and for borders and basins is:

$$z = k\tau^a + f_o\tau \tag{III-15}$$

It should be noted that k will have different values in Eqs. III-13 and Eq. III-15 due to the width implied as will the values of K in Eqs. III-12 and III-14. For this manual, it will be assumed that the exponent, a, has the same value for both furrow and border/basin irrigation.

The cumulative intake in furrow can be expressed as an equivalent depth by:

$$z = Z/w \tag{III-16}$$

where w is the furrow spacing. However, Eq. III-16 assumes complete later uniformity between furrows which is generally not the case. Nevertheless it is often convenient to express the required intake necessary to refill the root zone as a depth, z_{req}, and then determine the corresponding required furrow intake Z_{req} using Eq. III-16. One note of caution is that Eq. III-16 does not imply that $k=K/w$ or that $f_o=F_o/w$. These relations are described below.

Since surface irrigation is often applied to the heavier soils and some of these tend to crack, Eqs. III-14 and III-15 can be extended to include a combined term for cracking and depression storage, c, C:

$$z = k\tau^a + f_o\tau + c \tag{III-17}$$

$$Z = K\tau^a + F_o\tau + C \qquad \text{(III-18)}$$

The units of c and C are the same as z and Z, respectively. To date, there are no general recommendations for the cracking terms.

One can observe that if f_o is set to zero, Eq. III-17 has the same form as the NRCS infiltration family equations:

$$z = k\tau^a + c \qquad \text{(III-19)}$$

III.2.2.2 Revised NRCS Intake Families

The original SCS intake families, based on Eq. III.19 with a fixed c value, have provided users with a starting point in the design and evaluation of surface irrigation systems. These original intake family curves are revised in this manual to correspond to Eqs. III-14 and III-15. In order to provide the revised families that are typical of values found in field measurements, there are several assumptions that have been made.

1. The availability of data in the form of Eqs. III-14 and III-15 is much greater for furrow systems than for either borders or basins. Consequently, the reference family structure is formulated for furrow irrigation and then modified for borders and basins.

2. The intake families should encompass both initial and later irrigations since the intake characteristics are usually reduced after the first irrigation. The reference family of curves is for the initial irrigations. Changes due to previous irrigations have been estimated from field experience and expressed as a modification of the reference family.

3. The intake families are denoted with numbers varying from 0.02 to 4.00. These family categories are the average infiltration rate over the first six hours of irrigation. For initial continuous flow irrigations the average 6-hour intake rate is essentially the same as the family designation, but 6-hour intake rates for subsequent irrigations are less. The Table III-2 below shows the average 6-hour intake rates for each soil and irrigation regime.[5]

4. The effect of surge flow for initial irrigations is approximately the same as the effect of previous irrigations under continuous flow. Intake under surge flow systems during subsequent irrigations is based on adjustment of the initial irrigation surge flow intake.

5. It has been assumed that the exponent a in Eqs. III-14 and III-15 are the same value, i.e., the a exponent is the same for furrow and border/basins for each soil.

A comparison of the total 6-hour cumulative intake for the reference family and the three other furrow irrigated conditions is shown in Fig. III-4. The intake parameters for furrows are shown in Tables III-3 – III-6.

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[5] A review of how the original SCS intake families were developed is included in Appendix A.

TABLE III-2. AVERAGE 6-HOUR INTAKE RATES FOR THE FURROW-BASED REFERENCE INTAKE FAMILIES.

NRCS Curve No.	Soil Type	Initial Continuous Flow Irrig. 6-hour Intake Rate, in/hr	Later Continuous Flow Irrig. 6-hour Intake Rate, in/hr	Initial Surge Flow Irrig. 6-hour Intake Rate, in/hr	Later Surge Flow Irrig. 6-hour Intake Rate, in/hr
0.02	**Heavy Clay**	0.022	0.017	0.018	0.016
0.05	**Clay**	0.055	0.042	0.045	0.039
0.10	**Clay**	0.099	0.074	0.080	0.068
0.15	**Light Clay**	0.145	0.106	0.115	0.097
0.20	**Clay Loam**	0.193	0.138	0.150	0.126
0.25	**Clay Loam**	0.242	0.170	0.185	0.155
0.30	**Clay Loam**	0.292	0.202	0.221	0.183
0.35	**Silty**	0.343	0.234	0.256	0.211
0.40	**Silty**	0.395	0.265	0.291	0.239
0.45	**Silty Loam**	0.447	0.296	0.326	0.266
0.50	**Silty Loam**	0.500	0.326	0.361	0.293
0.60	**Silty Loam**	0.605	0.386	0.429	0.345
0.70	**Silty Loam**	0.710	0.445	0.495	0.396
0.80	**Sandy Loam**	0.815	0.501	0.560	0.445
0.90	**Sandy Loam**	0.918	0.556	0.624	0.492
1.00	**Sandy Loam**	1.021	0.610	0.686	0.538
1.50	**Sandy**	1.517	0.855	0.973	0.745
2.00	**Sandy**	1.994	1.074	1.234	0.926
4.00	**Sandy**	3.966	1.834	2.180	1.527
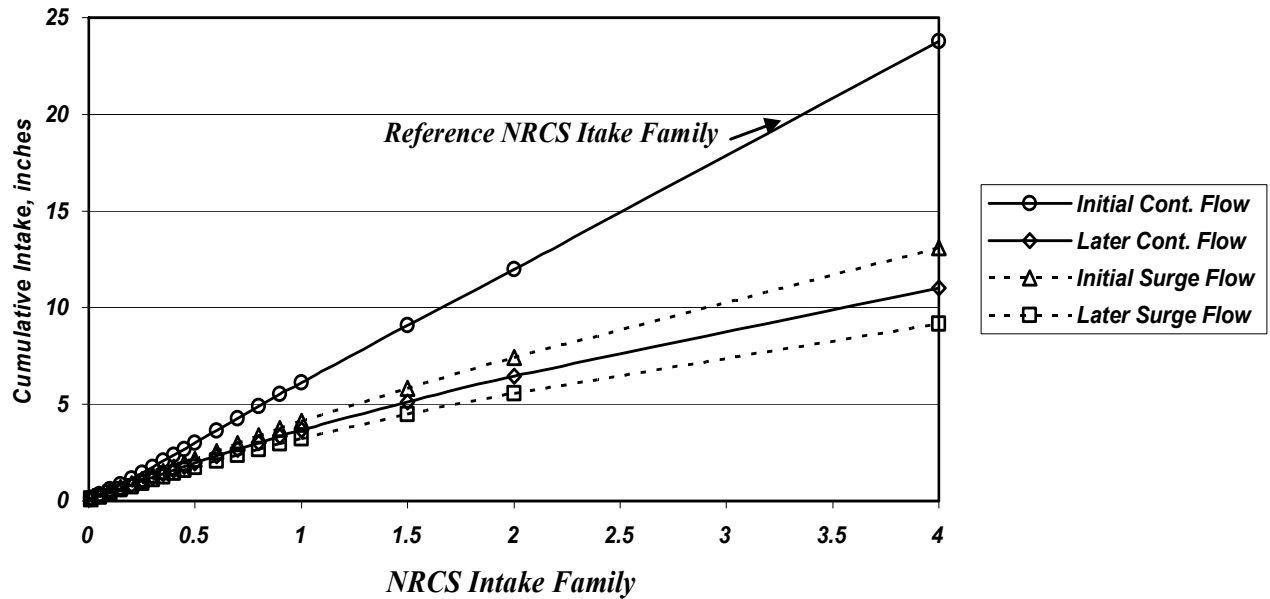
Figure III-4. Average 6-hour intake rate for the revised NRCS furrow intake families.

TABLE III-3. CONTINUOUS FLOW FURROW INTAKE FAMILIES – INITIAL IRRIGATIONS.

```
Continuous Flow Intake Curve Parameters for Initial Irrigations
   ID Soil Name        a          K            Fo          Qr       Vpr
                            (ft^3/ft/mn^a) (ft^3/ft/mn)  (gpm)     ( ft)
```

ID	Soil Name	a	K (ft^3/ft/mn^a)	Fo (ft^3/ft/mn)	Qr (gpm)	Vpr (ft)
.02	Heavy Clay	0.188	0.002420	0.0000786	7.411	0.365
.05	Clay	0.248	0.004466	0.0001981	8.255	0.399
.10	Clay	0.306	0.006823	0.0003369	9.648	0.452
.15	Light Clay	0.351	0.008710	0.0004704	11.023	0.500
.20	Clay Loam	0.387	0.010346	0.0005974	12.381	0.544
.25	Clay Loam	0.417	0.011807	0.0007212	13.721	0.586
.30	Clay Loam	0.442	0.013140	0.0008396	15.042	0.626
.35	Silty	0.463	0.014396	0.0009548	16.347	0.663
.40	Silty	0.481	0.015563	0.0010656	17.633	0.699
.45	Silty Loam	0.497	0.016671	0.0011733	18.901	0.733
.50	Silty Loam	0.512	0.017740	0.0012777	20.152	0.767
.60	Silty Loam	0.535	0.019730	0.0014768	22.599	0.830
.70	Silty Loam	0.555	0.021591	0.0016652	24.976	0.889
.80	Sandy Loam	0.571	0.023352	0.0018417	27.281	0.945
.90	Sandy Loam	0.585	0.025004	0.0020096	29.514	0.999
1.00	Sandy Loam	0.597	0.026596	0.0021679	31.677	1.050
1.50	Sandy	0.641	0.033670	0.0028384	41.420	1.282
2.00	Sandy	0.671	0.039806	0.0033508	49.381	1.483
4.00	Sandy	0.749	0.059571	0.0044606	63.401	2.131

TABLE III-4. CONTINUOUS FLOW FURROW INTAKE FAMILIES – LATER IRRIGATIONS.

```
Continuous Flow Intake Curve Parameters for Later Irrigations
   ID Soil Name        a          K            Fo          Qr       Vpr
                            (ft^3/ft/mn^a) (ft^3/ft/mn)  (gpm)     ( ft)
```

ID	Soil Name	a	K (ft^3/ft/mn^a)	Fo (ft^3/ft/mn)	Qr (gpm)	Vpr (ft)
.02	Heavy Clay	0.151	0.002060	0.0000624	7.411	0.365
.05	Clay	0.198	0.003786	0.0001582	8.255	0.399
.10	Clay	0.245	0.005803	0.0002702	9.648	0.452
.15	Light Clay	0.281	0.007410	0.0003757	11.023	0.500
.20	Clay Loam	0.310	0.008786	0.0004779	12.381	0.544
.25	Clay Loam	0.334	0.010037	0.0005769	13.721	0.586
.30	Clay Loam	0.353	0.011170	0.0006717	15.042	0.626
.35	Silty	0.370	0.012236	0.0007632	16.347	0.663
.40	Silty	0.385	0.013233	0.0008525	17.633	0.699
.45	Silty Loam	0.398	0.014181	0.0009386	18.901	0.733
.50	Silty Loam	0.409	0.015070	0.0010215	20.152	0.767
.60	Silty Loam	0.428	0.016770	0.0011819	22.599	0.830
.70	Silty Loam	0.444	0.018351	0.0013315	24.976	0.889
.80	Sandy Loam	0.457	0.019842	0.0014736	27.281	0.945
.90	Sandy Loam	0.468	0.021254	0.0016071	29.514	0.999
1.00	Sandy Loam	0.478	0.022606	0.0017341	31.677	1.050
1.50	Sandy	0.513	0.028620	0.0022712	41.420	1.282
2.00	Sandy	0.537	0.033846	0.0026802	49.381	1.483
4.00	Sandy	0.599	0.050631	0.0035693	63.401	2.131

TABLE III-5. SURGE FLOW FURROW INTAKE FAMILIES – INITIAL IRRIGATIONS.

Surge Flow Intake Curve Parameters for Initial Irrigations

ID Soil Name		a	K ($ft^3/ft/mn^a$)	Fo ($ft^3/ft/mn$)	Qr (gpm)	Wpr (ft)
.02	Heavy Clay	0.160	0.002120	0.0000667	7.411	0.365
.05	Clay	0.211	0.003906	0.0001679	8.255	0.399
.10	Clay	0.260	0.005973	0.0002863	9.648	0.452
.15	Light Clay	0.298	0.007620	0.0003993	11.023	0.500
.20	Clay Loam	0.329	0.009046	0.0005081	12.381	0.544
.25	Clay Loam	0.354	0.010327	0.0006125	13.721	0.586
.30	Clay Loam	0.376	0.011500	0.0007136	15.042	0.626
.35	Silty	0.394	0.012586	0.0008116	16.347	0.663
.40	Silty	0.409	0.013623	0.0009052	17.633	0.699
.45	Silty Loam	0.423	0.014591	0.0009967	18.901	0.733
.50	Silty Loam	0.435	0.015520	0.0010861	20.152	0.767
.60	Silty Loam	0.455	0.017270	0.0012551	22.599	0.830
.70	Silty Loam	0.472	0.018891	0.0014155	24.976	0.889
.80	Sandy Loam	0.485	0.020422	0.0015661	27.281	0.945
.90	Sandy Loam	0.497	0.021874	0.0017082	29.514	0.999
1.00	Sandy Loam	0.508	0.023266	0.0018428	31.677	1.050
1.50	Sandy	0.545	0.029460	0.0024133	41.420	1.282
2.00	Sandy	0.570	0.034836	0.0028481	49.381	1.483
4.00	Sandy	0.637	0.052121	0.0037921	63.401	2.131

TABLE III-6. SURGE FLOW FURROW INTAKE FAMILIES – LATER IRRIGATIONS.

Surge Flow Intake Curve Parameters for Later Irrigations

ID Soil Name		a	K ($ft^3/ft/mn^a$)	Fo ($ft^3/ft/mn$)	Qr (gpm)	Wpr (ft)
.02	Heavy Clay	0.141	0.001940	0.0000592	7.411	0.365
.05	Clay	0.186	0.003566	0.0001485	8.255	0.399
.10	Clay	0.229	0.005463	0.0002530	9.648	0.452
.15	Light Clay	0.263	0.006980	0.0003531	11.023	0.500
.20	Clay Loam	0.290	0.008276	0.0004489	12.381	0.544
.25	Clay Loam	0.313	0.009447	0.0005403	13.721	0.586
.30	Clay Loam	0.331	0.010520	0.0006297	15.042	0.626
.35	Silty	0.347	0.011516	0.0007158	16.347	0.663
.40	Silty	0.361	0.012443	0.0007987	17.633	0.699
.45	Silty Loam	0.373	0.013341	0.0008794	18.901	0.733
.50	Silty Loam	0.384	0.014190	0.0009580	20.152	0.767
.60	Silty Loam	0.401	0.015780	0.0011076	22.599	0.830
.70	Silty Loam	0.416	0.017281	0.0012486	24.976	0.889
.80	Sandy Loam	0.428	0.018682	0.0013810	27.281	0.945
.90	Sandy Loam	0.439	0.020004	0.0015069	29.514	0.999
1.00	Sandy Loam	0.448	0.021276	0.0016254	31.677	1.050
1.50	Sandy	0.481	0.026940	0.0021291	41.420	1.282
2.00	Sandy	0.503	0.031856	0.0025134	49.381	1.483
4.00	Sandy	0.562	0.047651	0.0033454	63.401	2.131

To determine the Kostiakov-Lewis parameters for border and basin irrigation, it has been assumed that the infiltration through the furrow perimeter is uniform and that the *a* exponent is the same for both situations. Recognizing that one-dimensional border/basin infiltration will be different per unit width than in furrow, a reference wetted perimeter for each furrow family has been defined that is intended to compensate for these differences. Figure III-5 shows typical values of wetted perimeter for furrow irrigation in each of the soil families. These values will change with slope, roughness, crop, and cultural practice and are therefore only for reference purposes. To convert from furrows to borders or basins, the furrow *K* and *F_o* coefficients are divided by the reference wetted perimeter. Tables for initial and later border and basin irrigation under both continuous and surged flow are given in Tables III-7 to III-10.

Reference Furrow Wetted Perimeter
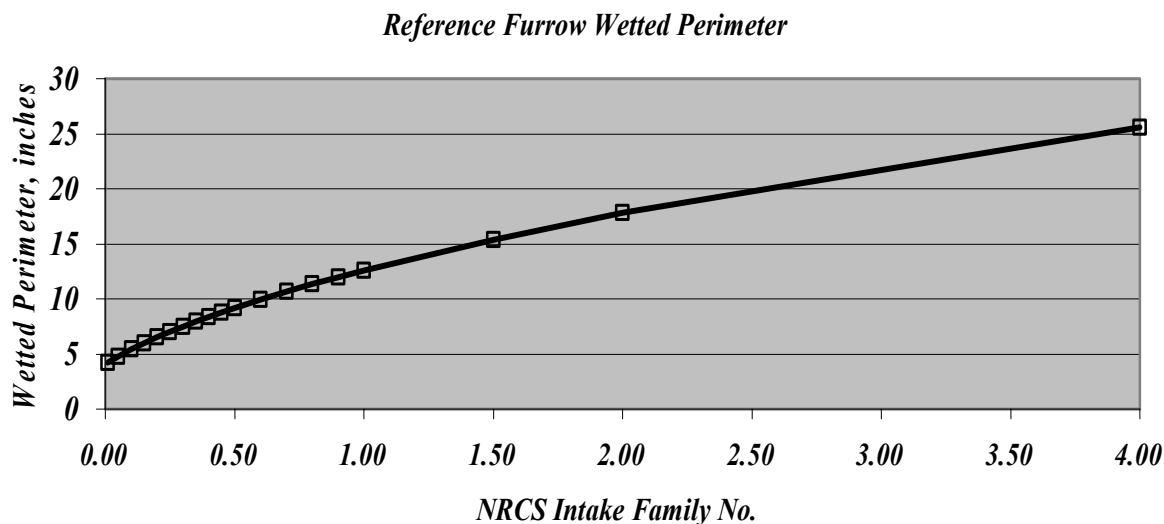
Figure III-5. Reference wetted perimeters for the revised NRCS intake families.

It is also necessary to specify a reference discharge for the furrow irrigation families since furrow intake is proportional to the wetted perimeter and must be adjusted based on the actual flow in the furrow. The values of the reference wetted perimeter and flow are given in Tables III-3 – III-6. Figure III-6 shows the relationship of reference flow to intake family.

Reference Furrow Dischage
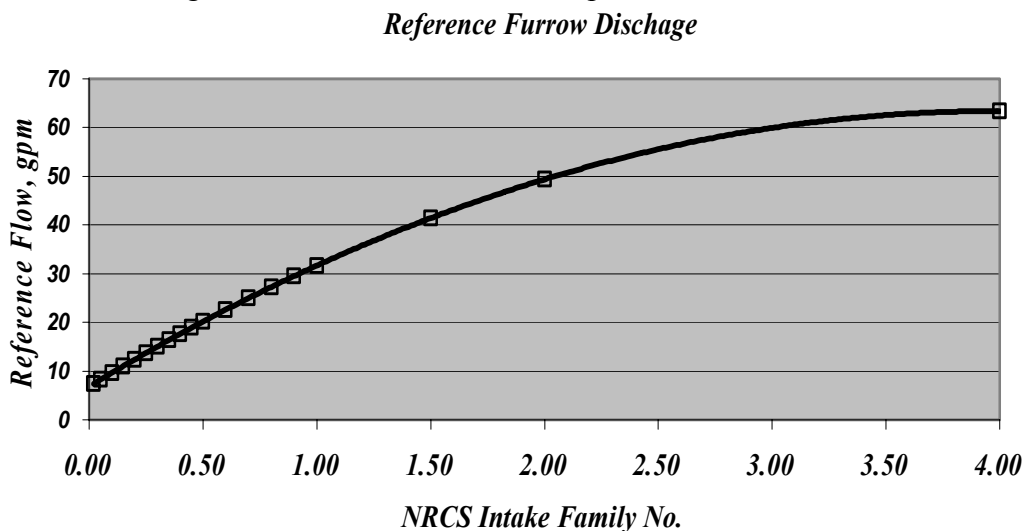
Figure III-6. Reference flow for the NRCS intake families.

**TABLE III-7. CONTINUOUS FLOW BORDER/BASIN INTAKE FAMILIES –
INITIAL IRRIGATIONS.**

Continuous Flow Intake Curve Parameters for Initial Irrigations

ID	Soil Name	a	k (ft/mn^a)	fo (ft/mn)
.02	Heavy Clay	0.188	0.006640	0.0002155
.05	Clay	0.248	0.011176	0.0004963
.10	Clay	0.306	0.015113	0.0007458
.15	Light Clay	0.351	0.017420	0.0009411
.20	Clay Loam	0.387	0.019006	0.0010974
.25	Clay Loam	0.417	0.020137	0.0012303
.30	Clay Loam	0.442	0.021010	0.0013420
.35	Silty	0.463	0.021706	0.0014397
.40	Silty	0.481	0.022273	0.0015244
.45	Silty Loam	0.497	0.022731	0.0015996
.50	Silty Loam	0.512	0.023140	0.0016666
.60	Silty Loam	0.535	0.023780	0.0017799
.70	Silty Loam	0.555	0.024291	0.0018729
.80	Sandy Loam	0.571	0.024702	0.0019482
.90	Sandy Loam	0.585	0.025034	0.0020116
1.00	Sandy Loam	0.597	0.025316	0.0020637
1.50	Sandy	0.641	0.026270	0.0022143
2.00	Sandy	0.671	0.026846	0.0022590
4.00	Sandy	0.749	0.027951	0.0020930

**TABLE III-8. CONTINUOUS FLOW BORDER/BASIN INTAKE FAMILIES –
LATER IRRIGATIONS.**

Continuous Flow Intake Curve Parameters for Later Irrigations

| ID	Soil Name	a	k (ft/mn^a)	fo (ft/mn)
.02	Heavy Clay	0.151	0.005640	0.0001713
.05	Clay	0.198	0.009476	0.0003965
.10	Clay	0.245	0.012843	0.0005981
.15	Light Clay	0.281	0.014820	0.0007516
.20	Clay Loam	0.310	0.016136	0.0008779
.25	Clay Loam	0.334	0.017117	0.0009843
.30	Clay Loam	0.353	0.017860	0.0010736
.35	Silty	0.370	0.018446	0.0011508
.40	Silty	0.385	0.018923	0.0012195
.45	Silty Loam	0.398	0.019331	0.0012797
.50	Silty Loam	0.409	0.019660	0.0013324
.60	Silty Loam	0.428	0.020210	0.0014245
.70	Silty Loam	0.444	0.020641	0.0014976
.80	Sandy Loam	0.457	0.020982	0.0015588
.90	Sandy Loam	0.468	0.021274	0.0016086
1.00	Sandy Loam	0.478	0.021526	0.0016508
1.50	Sandy	0.513	0.022330	0.0017718
2.00	Sandy	0.537	0.022826	0.0018069
4.00	Sandy	0.599	0.023761	0.0016748

TABLE III-9. SURGE FLOW BORDER/BASIN INTAKE FAMILIES – INITIAL IRRIGATIONS.

Surge Flow Intake Curve Parameters for Initial Irrigations

ID	Soil Name	a	k (ft/mn^a)	fo (ft/mn)
.02	Heavy Clay	0.160	0.005820	0.0001831
.05	Clay	0.211	0.009766	0.0004208
.10	Clay	0.260	0.013223	0.0006338
.15	Light Clay	0.298	0.015250	0.0007990
.20	Clay Loam	0.329	0.016616	0.0009333
.25	Clay Loam	0.354	0.017617	0.0010449
.30	Clay Loam	0.376	0.018370	0.0011407
.35	Silty	0.394	0.018976	0.0012238
.40	Silty	0.409	0.019483	0.0012950
.45	Silty Loam	0.423	0.019881	0.0013589
.50	Silty Loam	0.435	0.020250	0.0014166
.60	Silty Loam	0.455	0.020810	0.0015127
.70	Silty Loam	0.472	0.021251	0.0015921
.80	Sandy Loam	0.485	0.021602	0.0016567
.90	Sandy Loam	0.497	0.021894	0.0017099
1.00	Sandy Loam	0.508	0.022146	0.0017543
1.50	Sandy	0.545	0.022980	0.0018826
2.00	Sandy	0.570	0.023486	0.0019201
4.00	Sandy	0.637	0.024461	0.0017793

TABLE III-10. SURGE FLOW BORDER/BASIN INTAKE FAMILIES – LATER IRRIGATIONS.

Surge Flow Intake Curve Parameters for Later Irrigations

ID	Soil Name	a	k (ft/mn^a)	fo (ft/mn)
.02	Heavy Clay	0.141	0.005310	0.0001624
.05	Clay	0.186	0.008936	0.0003722
.10	Clay	0.229	0.012083	0.0005599
.15	Light Clay	0.263	0.013950	0.0007064
.20	Clay Loam	0.290	0.015196	0.0008245
.25	Clay Loam	0.313	0.016107	0.0009218
.30	Clay Loam	0.331	0.016810	0.0010065
.35	Silty	0.347	0.017356	0.0010793
.40	Silty	0.361	0.017803	0.0011425
.45	Silty Loam	0.373	0.018181	0.0011989
.50	Silty Loam	0.384	0.018500	0.0012496
.60	Silty Loam	0.401	0.019020	0.0013349
.70	Silty Loam	0.416	0.019431	0.0014044
.80	Sandy Loam	0.428	0.019752	0.0014608
.90	Sandy Loam	0.439	0.020024	0.0015084
1.00	Sandy Loam	0.448	0.020256	0.0015473
1.50	Sandy	0.481	0.021020	0.0016609
2.00	Sandy	0.503	0.021476	0.0016945
4.00	Sandy	0.562	0.022361	0.0015697

III.2.3 Irrigation Efficiency and Uniformity

The effectiveness of irrigation can be described by its efficiency and uniformity. Because an irrigation system applies water for evapotranspiration and leaching needs as well as occasionally seed bed preparation, germination, or cooling there have emerged a number of different efficiencies and ratios to give specific measures of performance. The most important indicator of how well the irrigation served its purposes is how it impacted production and profitability on the farm.

When a field with a uniform slope, soil and crop receives steady flow at its upper end, a water front will advance at a monotonically decreasing rate until it reaches the end of the field. If it is not diked, runoff will occur for a time before recession starts following cutoff. Figure III-7 shows the distribution of applied water along the field length stemming from these assumptions. The differences in applied depths are non-uniformly distributed with a characteristic shape skewed toward the inlet end of the field.
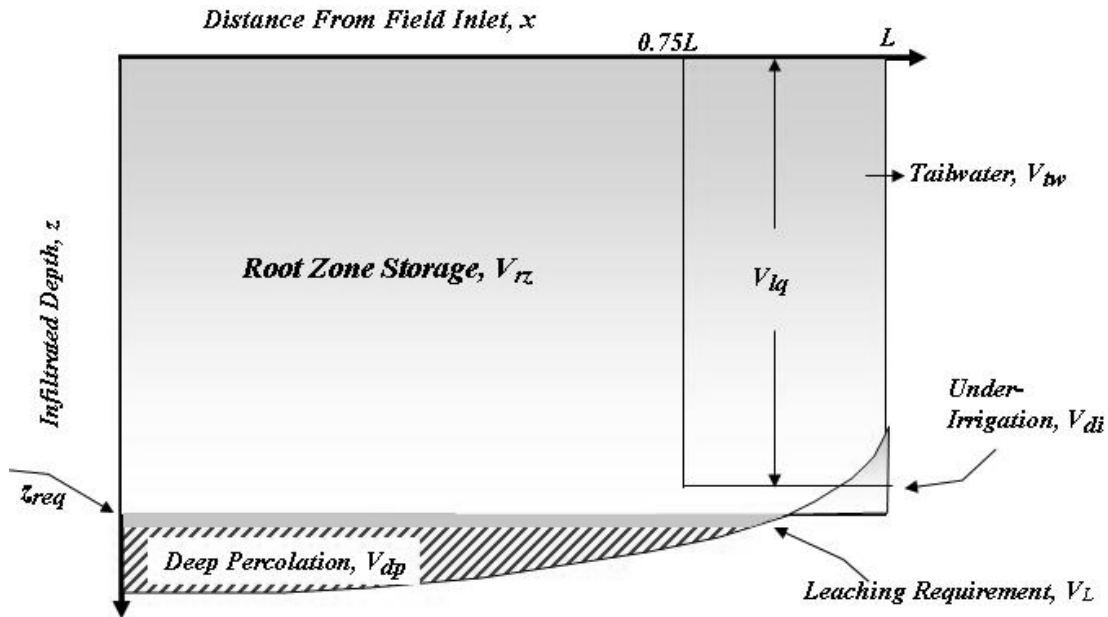
Figure III-7. Distribution of applied water in surface irrigation.

The amount of water that can be stored in the root zone is $L \times z_{req}$, but as shown, some region of the root zone has not received water owing to the spatial distribution of infiltration. The depth of water that would refill the root zone is z_{req}, beyond which water percolates below the roots and is "lost" to the drainage or groundwater system. Generally these flows return to receiving waters where they can be used elsewhere. Thus, they are lost in terms of the local condition but perhaps not to the regional or basin locale. The negative connotations of loss should be kept even though this water may be recovered and reused. The quality of these flows is nearly always degraded and the timing of when they are available elsewhere may not be useful.

Computing each of these components requires a numerical integration of infiltrated depth over the field length. For the purposes of this discussion, it is convenient to define the components as follows:

V_{in} is the total depth (per unit width) or volume (per furrow spacing) of water applied to the field.

V_{RZ} is the total depth (per unit width) or volume (per furrow spacing) of water necessary to replace the soil moisture deficit.

V_{rz} is the depth of water (per unit width) or volume (per furrow spacing) of irrigation water that is actually stored in the root zone.

V_{di} is the depth of water (per unit width) or volume (per furrow spacing) that represents under-irrigation.

V_{dp} is the depth of water (per unit width) or volume (per furrow spacing) of water that percolates below the root zone.

V_{tw} is the depth of water (per unit width) or volume (per furrow spacing) of water that flows from the field as tailwater.

V_L is the depth of water (per unit width) or volume of (per furrow spacing) of water needed for leaching.

V_{lq} is the average depth (per unit width) or volume (per furrow spacing) of infiltrated water in the least-irrigated 25% of the field.

III.2.3.1   Irrigation Efficiency

The definition of irrigation efficiency, E_i, represents the fraction of water applied to the field that could be considered beneficially used:

$$E_i = \frac{V_{rz} + V_L}{V_{in}} = \frac{V_{rz} + V_L}{V_{rz} + V_{dp} + V_{tw}}$$

(III-20))

III.2.3.2   Application Efficiency

Application efficiency is a subset of irrigation efficiency which evaluates only how well the irrigation water was stored in the root zone:

$$E_a = \frac{V_{rz}}{V_{in}} = \frac{V_{rz}}{V_{rz} + V_{dp} + V_{tw}}$$

(III-21)

III.2.3.3   Storage or Requirement Efficiency

A measure of how well the root zone was refilled is called storage or requirement efficiency and is described as:

$$E_r = \frac{V_{rz}}{V_{RZ}} = \frac{V_{rz}}{z_{req} \cdot w \cdot L}$$

(III-22)

III.2.3.4   Distribution Uniformity

Application or distribution uniformity concerns the distribution of water over the actual field and can be defined as the infiltrated depth or volume in the least-irrigated 25% of the field divided by the infiltrated depth or volume over the whole field:

$$DU = \frac{4.0 \cdot V_{lq}}{\left(V_{rz} + V_{dp} \right)} \qquad \text{(III-23)}$$

III.2.3.5 Deep Percolation Ratio

The deep percolation ratio indicates the fraction of applied irrigation water infiltrating the soil that percolates below the root zone:[6]

$$DPR = \frac{V_{dp}}{V_{in}} = \frac{V_{dp}}{V_{rz} + V_{dp} + V_{tw}} \qquad \text{(III-24)}$$

III.2.3.6 Tailwater Ratio

The tailwater ratio is the fraction of irrigation water applied to the field that runs off as tailwater:

$$TWR = \frac{V_{tw}}{V_{in}} = \frac{V_{tw}}{V_{rz} + V_{dp} + V_{tw}} \qquad \text{(III-25)}$$

III.2.3.7 Example

A furrow-irrigated set consists of 27 furrows spaced 30 in. apart with a furrow length of 1320 ft. At the time that the irrigation event was begun, the soil moisture deficit was 4.3 in. The estimated leaching requirement was 0.4 inches. Each furrow had an inflow of 13 gpm for 24 hours. The distribution of infiltrated water depth along the furrow length was as follows:

Furrow length, l/L	.05	.15	.25	.35	.45	.55	.65	.75	.85	.95
Infiltrated depth (in)	6.2	6.0	5.8	5.6	5.4	5.1	4.8	4.3	3.7	3.0

What were the values of the various efficiencies and uniformities for this irrigation event?

In most field evaluations, the volume of tailwater will be measured. The exception of course is for the case of basins or blocked-end borders where runoff is restricted. In this case the volume of tailwater is not given and must be computed.

The first step is to estimate the total volume of water that has infiltrated the soil from the data above. One way is to determine a best fit line through the data, and integrate the function, multiply by the furrow spacing (2.5 ft) and length. Another is simply to average the depths, multiply by the furrow spacing and then by the total field length. The result of a sophisticated numerical analysis is a total intake of 1,366 ft³ and that of simple averaging is 1,372 ft³.

The volume of inflow to each furrow was 13 gpm for 24 hours which translates to 2,502 ft³. The total tailwater is therefore 2,502-1366 = 1136 ft³, or the **TWR** from Eq. III-25 is 0.454 or 45.4%.

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[6] Note that precipitation during the irrigation event and perhaps within 1-3 days will also contribute to the total amount of water percolating below the root zone. The deep percolation ratio is intended as a quantitative measure of irrigation performance and does not include precipitation and thus may not represent all the deep percolation that occurs.

The next question is how much deep percolation occurred? Analyses based on a numerical procedure are very helpful for this computation since a partial integration is necessary. One could estimate the deep percolation graphically as well. Using the more elaborate analysis, the intake profile is integrated between 0 and 990 feet at which point the intake is less than the soil moisture deficit and it is assumed that no deep percolation occurs. This yields a total intake over the portion of field where deep percolation occurs of 1,226 ft^3, of which 886 ft^3 are captured in the root zone (990 feet * 4.3 inches * 2.5 ft /12 in/ft). The total estimated volume of deep percolation is therefore 340 ft^3, or **DPR** = 340/2502 = 0.136, or 13.6%.

The total intake in the last 330 feet of furrow can be calculated similarly and should equal about 140 ft^3 making the total water stored in the root zone 1,026 ft^3 (140 + 886). The application efficiency, E_a, from Eq. III-21 is therefore 1,026/2502 = 0.410, or 41.0%.

The sum of application efficiency, E_a, the tailwater ratio, **TWR**, and the deep percolation ratio, **DPR** should total to 100%. In this case the total is 100%.

If the root zone had been completely refilled, the volume there would have been 1,183 ft^3 (4.3 inches * 1320 ft * 2.5 ft). Since only 1,026 ft^3 was stored, the storage or requirement efficiency, E_r, from Eq. III-22 is 1,026/1,183 = 0.8756 or 87.6%.

The distribution uniformity, **DU**, can now be found from Eq. III-23 as 4*140/1366 = 0.410, or 4110%.

This is a very poor irrigation and would be a candidate for much better management and/or design. However, some improvement in the numbers at least is possible by including the leaching in the evaluation. An approximate volume of leaching can be found by assuming leaching occurs wherever deep percolation occurs, in this case over the first 990 feet of the furrow. The volume of leaching is therefore 0.4 inches * 990 ft * 2.5 ft /12 = 82.5 ft^3. The irrigation efficiency from Eq. III-20 is (1125+82.5)/2502 = 0.483, or 48.3%.

III.2.4 Water Measurement

One of the simplest and yet most important concepts in surface irrigation can be described mathematically as follows:

$$Q_T T_T = DA \tag{III-26}$$

where: Q_T = Total flow delivered to the field;
T_T = Total time the flow, Q_T, is delivered to the field;
D = Depth of water applied to the field; and
A = Area of the field.

As an example, if it requires a flow of 10 cfs for 48 hours to irrigate a field of 40 acres, the depth that will be applied will be about 12 inches. The flow rate delivered to a field is critically important in two respects. First, the surface irrigation system is highly sensitive to the flow because it determines how fast or slow the field will be irrigated. And secondly, the efficient surface irrigator must judge the effectiveness of his management by planning a target depth of application for each irrigation and then assessing the performance of the system as it operates. In both cases a significant difference between the flow necessary to apply the appropriate depth in the planned period and the actual flow delivered will adversely impact the

efficiency and uniformity of the surface irrigation. Flow measurement is vitally important in surface irrigation.

The NRCS uses the "Water Measurement Manual" of the Bureau of Reclamation, U.S. Department of the Interior as its water measurement guide (Section 15, Chapter 9, National Engineering Handbook). This manual is also available from your state irrigation specialist or IT personnel, or can be downloaded directly from:

http://www.usbr.gov/pmts/hydraulics_lab/ pubs/index.html

III.3   FIELD EVALUATIONS

III.3.1 Standard Field Evaluation Procedure

The basic objective of a surface irrigation field evaluation is to establish a water balance for the field and thereby identify each of the components necessary to determine the efficiencies and uniformities noted in Eqs. III-20 through III-25. Standard practices are developed in other NRCS manuals[7]. and will not repeated here in detail   However, based on recent experience, a number of simplifications and modifications can be suggested.

III.3.1.1   Flow Shape

In order to estimate flow depths it is necessary to describe the shape of the flow cross-section. For borders and basins this shape is generally assumed to be a wide rectangular sheet which can be evaluated by examining a unit width within the border or basin. In furrow irrigation, however, it is necessary to describe the actual shape so that relationships between depth and area and/or wetted perimeter can be calculated.

Furrow shapes are nearly always irregular but can be described using a series of power functions. The following analysis uses the Manning equation as the primary relationship between depth, slope, cross-section, and flow.

An expression relating wetted perimeter, *WP*, can be defined as a function of flow depth, *y*, as follows:

$$WP = \gamma_1 y^{\gamma_2} \qquad\qquad\qquad \text{(III-27)}$$

where γ_1 and γ_2 are numerical fitting parameters. Both wetted perimeter and depth should be expressed in feet. Similarly, a function of cross-sectional area, *A* in ft^2, and depth in ft can be expressed as:

$$A = \sigma_1 y^{\sigma_2} \qquad\qquad\qquad \text{(III-28)}$$

where again σ_1 and σ_2 are numerical fitting parameters. The top width, *T*, can be described as:

$$T = Cch \cdot y^{Cmh} \qquad\qquad\qquad \text{(III-29)}$$

It has been found that for most furrows the hydraulic section can be defined as:

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[7] NRCS National Engineering Handbook Part 652, National Irrigation Guide Template, Chapter 9 – Irrigation Water Management.

$$A^2 R^{4/3} = \rho_1 A^{\rho_2} \tag{III-30}$$

in which,

$$\rho_2 = \frac{10}{3} - \frac{4\gamma_2}{3\sigma_2} \tag{III-31}$$

and,

$$\rho_1 = \frac{\sigma_1^{10/3-\rho_2}}{\gamma_1^{4/3}} \tag{III-32}$$

The values of γ_1, σ_1, and *Cch* are equal to the unit width used to describe the flow. The parameter ρ_1 equals the unit width squared. The values of γ_2, σ_2, *Cmh*, and ρ_2 for borders and basins are 0.0, 1.0, 0.0, and 3.33, respectively. Values for furrows will be defined below.

Using the English form of the Manning equation, the cross-sectional flow area at the field inlet, A_o in ft^2, can be determined for any flow, Q_o in cfs and field slope, S_o, greater than about 0.00001 as follows:

$$A_o = \left[\frac{0.4529 \cdot Q_o^2 \cdot n^2}{S_o \cdot \rho_1} \right]^{1/\rho_2} \tag{III-33}$$

If the field has a slope less than 0.00001, then inlet area, A_o, will increase as the advance proceeds down the field and must be re-computed for each advance distance. For this case, the value of the field slope, S_o is replaced in Eq. III-33 by:

$$S_o = \frac{y_o}{x} \tag{III-34}$$

where $\mathbf{y_o}$ is the depth of flow, in ft, at the field inlet and $\mathbf{x}$ is the advance distance in ft.

Figure III-8 illustrates the basic border/basin and furrow shapes. Measuring a furrow cross section in the field involves four simple measurements: (1) the total depth of the furrow, Y_{max}; (2) the base width, *Base*; (3) the top width at the Y_{max} depth, T_{max}; and the furrow width at a depth of $Y_{max}/2$, T_{mid}. The units of Y_{max}, T_{max}, and T_{mid} are feet.[8]

The values of the furrow geometry, γ_1, γ_2, σ_1, *and* σ_2 can then be calculated as follows:

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[8] For convenience, the units used in the input boxes of the *SURFACE* software are inches. The values of γ_1, γ_2, σ_1, σ_2, ρ_1, and ρ_2 depend on the units used. In the *SURFACE* software, only the metric values are displayed.
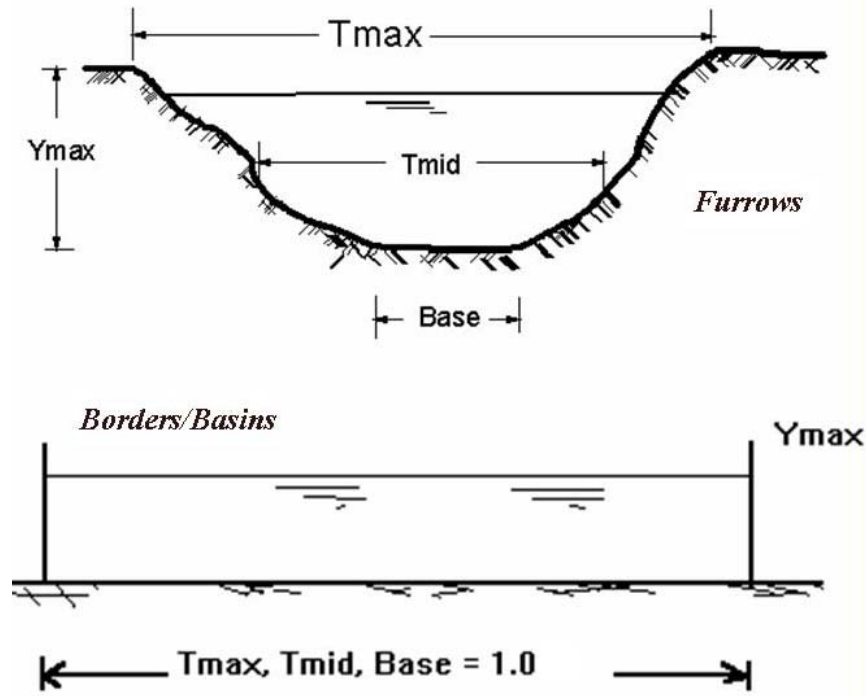
Figure III-8. Cross-sectional shapes for furrow and border/basin irrigation.

$$\gamma_2 = \frac{log\left[\dfrac{\left[Base + \sqrt{Y_{max}^2 + \left(T_{mid} - Base\right)^2} + \sqrt{Y_{max}^2 + \left(T_{max} - T_{mid}\right)^2}\right]}{\left[Base + \sqrt{Y_{max}^2 + \left(T_{mid} - Base\right)^2}\right]}\right]}{log2} \tag{III-35}$$

$$\gamma_1 = \frac{\left[Base + \sqrt{Y_{max}^2 + \left(T_{mid} - Base\right)^2} + \sqrt{Y_{max}^2 + \left(T_{max} - T_{mid}\right)^2}\right]}{Y_{max}^{\gamma_2}} \tag{III-36}$$

$$\sigma_2 = \frac{log\left[\dfrac{\dfrac{Y_{max}}{2}\left(\dfrac{Base}{2} + T_{mid} + \dfrac{T_{max}}{2}\right)}{\dfrac{Y_{max}}{2}\left(\dfrac{Base}{2} + \dfrac{T_{mid}}{2}\right)}\right]}{log2} \tag{III-37}$$
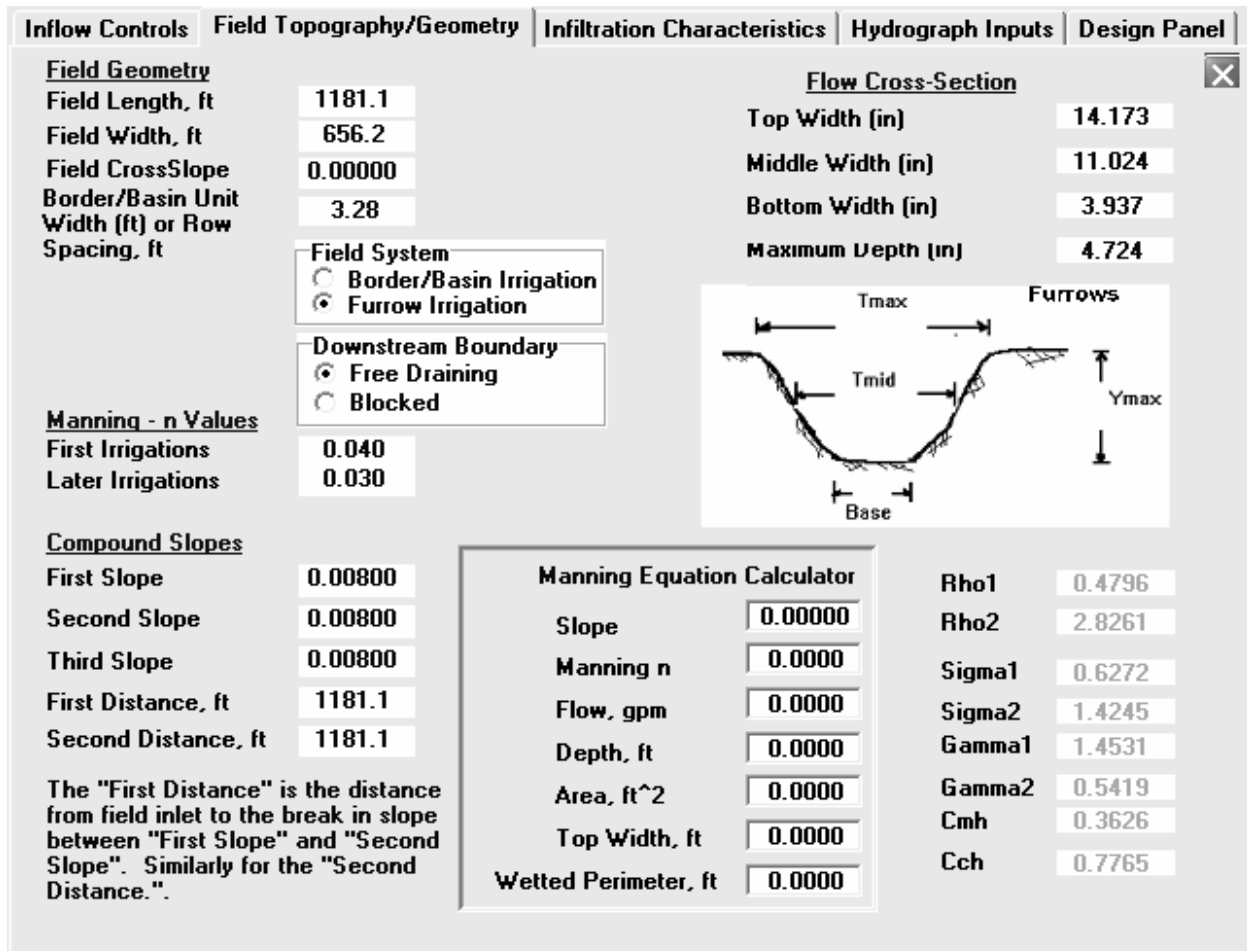
$$\sigma_1 = \frac{\dfrac{Y_{max}}{2}\left(\dfrac{Base}{2} + T_{mid} + \dfrac{T_{max}}{2}\right)}{Y_{max}^{\sigma_2}} \tag{III-38}$$

$$Cmh = \frac{log\left[\dfrac{T_{max}}{T_{mid}}\right]}{log[2]}$$ (III-39)

$$Cch = \frac{T_{max}}{y_{max}^{Cmh}}$$ (III-40)

III.3.1.2 Example

Rather than demonstrate these computations in a laborious example, the reader should open an application of the ***SURFACE*** software. From the main screen, click on the input data button, ⬛ , to open the input tabbed notebook with the software's default data set as shown in Fig. III-9 below.

Figure III-9. Example cross-section evaluation using the *SURFACE* software.

Make sure the field system is furrow irrigation by noting the checked ***Furrows*** radio button. Then enter 15.0 inches for the ***Top Width***, 12 inches for the ***Middle Width***, 2 inches for the ***Bottom Width***, and 4 inches for the ***Maximum Depth.*** As these numbers are entered, the

metric values are displayed in the boxes below labeled ***Rho1 –Cch*** and will change as Eqs. III-31 to III-32 and Eqs. III-35 to III-40 are executed by the software.

Suppose this furrow had a slope of 0.0001, a Manning ***n*** of 0.025, and was conveying a flow of 17 gpm. What would the depth, wetted perimeter, and cross-sectional area be? The answer can be found by entering the slope, Manning n, and flow in the ***Manning Equation Calculator*** as shown here. What would the flow depth be if the system was a border of the same slope? This can be determined by clicking on the ***Border/Basin*** check box and re-entering the slope, Manning n or the flow. The result will be 0.094 feet.

Manning Equation Calculator	
Slope	0.00010
Manning n	0.0250
Flow, gpm	17.0000
Depth, ft	0.2883
Area, ft^2	0.2113
Top Width, ft	1.0550
Wetted Perimeter, ft	1.2763

III.3.1.3   *Advance and Recession*

Most general evaluation procedures recommend that advance and recession be measured at several points along the field. However, these data do not provide sufficient information to justify the added labor associated with the evaluation and certainly not the problems associated with trafficking within the field. The readings that are most important are those shown in the advance-recession graph in Fig. III-10, namely: (1) the start time; (2) time of advance to the field midpoint; (3) the time of advance; (4) the time of cutoff; (5) the time of recession at the field inlet; (6) the recession time at the field midpoint; and (7) the time of recession.
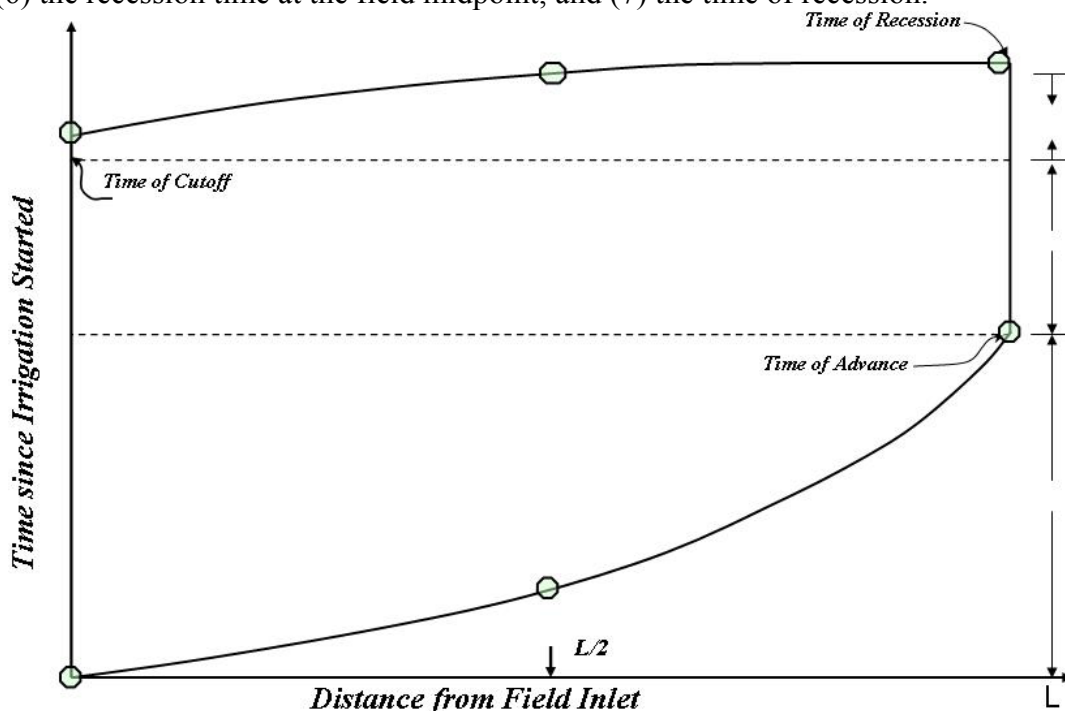
Figure III-10. Field measurement points for advance and recession evaluations in the field.

As a practical matter, the start time, time of advance, and recession time are all available from the inflow and outflow hydrographs if the field is free draining. Blocked end fields will require the recession time to be noted when the ponded water vanishes.

Two simple equations of advance and recession can be developed. For the advance trajectory, a simple power relationship is usually sufficient:

$$x = pt_x^r \tag{III-41}$$

in which:

$$r = \frac{log\left(\dfrac{L}{.5L}\right)}{log\left(\dfrac{t_L}{t_{.5L}}\right)} \tag{III-42}$$

and,

$$p = \frac{L}{t_L^r} \tag{III-43}$$

where,

x = the distance from the field inlet to the advancing front, ft;

t_x = time from the beginning of irrigation until the advancing front reaches the point x, min;

$t_{.5L}$ = the time from the beginning of irrigation until the advancing front reaches the field mid point, min;

t_L = the advance time, min;

L = the field length, ft; and

p, r = fitting coefficients.

The recession trajectory can be represented by a quadratic function:

$$\overline{t}_x = h + i \cdot x + j \cdot x^2 \tag{III-44}$$

in which:

$$h = \overline{t}_d \tag{III-45}$$

$$i = \frac{m^2 \overline{t}_L - \overline{t}_{.5L} - \overline{t}_d\left(m^2 - 1\right)}{L\left(m^2 - m\right)}, \; where \; m = \frac{.5L}{L} \tag{III-46}$$

$$j = \frac{\overline{t}_L - \overline{t}_d - i \cdot L}{L^2} \tag{III-47}$$

where,

$\overline{t}_x$ = the time of recession at a distance x from the field inlet, min;

$\overline{t}_d$ = the time of recession at the field inlet, sometimes called the time of depletion, min;

$\overline{t}_{.5L}$ = the time of recession at the field midpoint, min; and

$\overline{t}_L$ = the time of recession, min.

The intake opportunity time, τ, at any point x is defined as:

$$\tau = \overline{t}_x - t_x \tag{III-48}$$

III.3.1.4   *Example*

In the example data set labeled ***FreeDrainingFurrow_2.cfg,*** field data are reported for advance and recession measurements in the "Hydrographs Inputs" panel of the input tabbed notebook. Calculate the advance and recession curves for this field evaluation.

The advance curve represented by Eq. III-41 is determined as follows. The advance time to the midpoint of the field given by the station at 1013 feet is 116.0 minutes and the advance time to the end of the field at 2050.5 feet is 352.7 minutes. These numbers are show under the `Two-Point` button on the infiltration characteristics panel. They are also indicated in the "Advance and Recession" spreadsheet on the hydrograph inputs panel. The inflow is shutoff at 1440 minutes. The time of depletion, $\overline{t}_d$, at the inlet is 1444 minutes as shown at the recession time in the hydrograph inputs panel. The time of recession at 1013 feet, $\overline{t}_{.5L}$, along the furrow is 1482 minutes, and the recession time at the end of the furrow, $\overline{t}_L$, is 1502 minutes.

The value of *r* from Eq. III-42 is

$$r = \frac{log\left(\dfrac{L}{.5L}\right)}{log\left(\dfrac{t_L}{t_{.5L}}\right)} = \frac{log\left(\dfrac{2050.5}{1013}\right)}{log\left(\dfrac{352.7}{116.0}\right)} = .63413$$

The value of p is found from Eq. III-43:

$$p = \frac{L}{t_L^r} = \frac{2050.5}{352.7^{.63413}} = 49.70$$

The recession curve is defined by Eqs. III-44 to III-47:

$$h = \overline{t}_d = 1444 \ min$$

$$i = \frac{m^2\overline{t}_L - \overline{t}_{.5L} + \overline{t}_d\left(m^2 - 1\right)}{L\left(m^2 - m\right)}, \ where \ m = \frac{.5L}{L} = \frac{1013}{2050.5} = 0.494$$

$$i = \frac{.494^2\left(1502\right) - 1482 - 1444\left(.494^2 - 1\right)}{2050.5\left(.494^2 - .494\right)} = 0.04652$$

$$j = \frac{\overline{t}_L - \overline{t}_d - i \times L}{L^2} = \frac{1502 - 1444 - 0.04652 \times 2050.5}{2050.5^2} = -0.000008889$$

III.3.2 Infiltration

Not only is infiltration one of the most crucial hydraulic parameters affecting surface irrigation, but unfortunately, it is also one of the most difficult parameters to assess accurately in

the field. The importance of knowing the infiltration function in order to describe the hydraulics of a surface irrigation event, along with the inherent difficulties in obtaining reliable estimates of this parameter, means that the investigator should expect to spend considerable time and effort in assessing infiltration before proceeding with the design of a surface irrigation system.

In the past, the three most commonly employed techniques for measuring infiltration were cylinder infiltrometers, ponding, and inflow-outflow field measurements. For furrow irrigation, the blocked furrow method has been used, while a more recent technique is the flowing or recycling furrow infiltrometer.

III.3.2.1   Volume Balance Equation

An alternative to making individual point measurements of infiltration is to compute a representative intake from advance, recession, and the tailwater hydrograph, if available. This involves a two level iterative procedure. Assuming a furrow configuration for purposes of demonstration, the first level uses a volume balance computation:

$$60Q_o\, t_x = \sigma_y\, A_o\, x + \sigma_z\, Kt_x^a\, x + \frac{1}{(1+r)}F_o\, t_x\, x + Cx \qquad \text{(III-49)}$$

in which Q_o is the inflow per unit width or per furrow at the upstream end of the field in cfs; t_x is the time since inflow was initiated, in min; σ_y is the surface flow shape factor; A_o is the flow cross-sectional area at the flow's upstream end at time t_x, in ft^2; x is the distance from the inlet that the advancing front has traveled in t_x minutes, in ft; σ_z is the "subsurface shape factor" described by:

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+r)(1+a)} \qquad \text{(III-50)}$$

where **r** is the exponent in the power advance equation, Eq. III-41.

The value of σ_y is generally assumed to be constant with values between 0.75 and 0.80. However, its value actually changes with field slope, flow shape, slope of advance trajectory, and field length. At the time of the writing of this manual, no general guidelines were available for selecting a value of σ_y except that to assume it has a constant value of 0.77. A temporary estimation is provided as follows but users of this manual should be aware that new information will provide a better approximation in the future.

The flow velocity at the advancing front when it has reached the field midpoint can be found by differentiating Eq. III-41 and then dividing the result by the average velocity at the inlet to define a dimensionless velocity:

$$V_{.5L}^* = \frac{\dfrac{dx}{dt_x}}{V_o} = \frac{r\, p\, t_{.5L}^{r-1}}{Q_o/A_o} \qquad \text{(III-51)}$$

and when the advance has reached the end of the field:

$$V_L^* = \frac{\frac{dx}{dt_x}}{V_o} = \frac{r\,p\,t_L^{r-1}}{Q_o/A_o} \qquad \text{(III-52)}$$

The value of σ_y at both the midpoint and the field length can then be estimated as:

$$\sigma_{y|_{x=L}} = \frac{0.778}{1 + 0.363e^{-12.07V_L^*}} \qquad \text{(III-53)}$$

$$\sigma_{y|_{x=0.5L}} = \frac{0.778}{1 + 0.363e^{-12.07V_{.5L}^*}} \qquad \text{(III-54)}$$

III.3.2.2   *Volume Balance Estimate of Kostiakov a, K, and F_o*

Data from the field evaluation will have defined Q_o (and therefore A_o), as well as $t_{.5L}$, t_L (and therefore r, $V_{.5L}^*$, V_L^*, and σ_y). The unknowns in Eq. III-49 are the intake parameters a, K, and F_o (or a, k, f_o, and c if the border/basin evaluation is being conducted). The value of the cracking term c or C, must be input separately if it is known. Solving for these in Eq. III-49 provides the methodology for evaluating the average infiltration function along the length of a field using basic evaluation data.

As noted above, the procedure for finding intake parameter is iterative. The steps are as follows for furrow systems specifically and are the same for border/basin systems with the appropriate intake parameters (Note that the software accomplished these steps interactively as will be demonstrated below.):

1.   Assume an initial value of F_o to be zero. Equation III-49 can then be solved for any distance from the field inlet to define the volume balance at any time during the advance phase, but perhaps the two most important are the distance from the inlet to the field midpoint and to the end of the field. Doing so, but consolidating known terms on the right hand side yields the following two volume balance expressions:

$$\sigma_z\,Kt_L^a = \frac{Q_o\,t_L - \sigma_y\,A_{o|x=L}\,L - \frac{1}{1+r}F_o t_L\,L}{L} = I_L \qquad \text{(III-55)}$$

and

$$\sigma_z Kt_{.5L}^a = \frac{Q_o t_{.5L} - \sigma_y\,A_{o|x=.5L}\,(.5L) - \frac{1}{1+r}F_o\,t_{.5L}(.5L)}{.5L} = I_{.5L} \qquad \text{(III-56)}$$

Taking the log of both equations provides a definition of a and K as follows:

$$a = \frac{log\left(\frac{I_L}{I_{.5L}}\right)}{log\left(\frac{t_L}{t_{.5L}}\right)} \qquad \text{(III-57)}$$

Then r is computed from Eq. III-37 in order to find σ_z from Eq. III-50. Then K is found by substitution back into Eq. III-55:
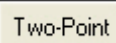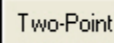
$$K = \frac{I_L}{\sigma_z t_L^a}$$

(III-58)

2.   Select 10-20 points along the field length, including the inlet and field end, and compute the depth of infiltration at each point using Eq. III-15 (the Kostiakov –Lewis equation) with the a, K, and F_o parameters available from Step 1 along with the intake opportunity time, τ, from Eq. III-48.   Then determine the total volume of infiltrated water as demonstrated in subsection III-2.3.7.

3.   The total volume of infiltration computed in Step 2 should equal the volumetric difference between the inflow and outflow hydrographs for free draining systems or the total inflow for blocked end systems. This is unlikely for the first iteration unless the value of F_o is indeed the assumed value. Generally, the volume of infiltration calculated in the first iteration will be too low and F_o will need to be increased. If F_o is initially set to zero and the resulting volume of infiltration from Steps 1-3 above is too low, the values of a, K, and F_o are as good as the volume balance can provide. A revised value of F_o should be made based on the error in the infiltrated volume and steps one, two and three repeated using revised values of the Kostiakov-Lewis parameters. When the least error is produced, the best estimate of the average field intake has been made with the volume balance methodology.

III.3.2.3   *Example*

To demonstrate this procedure, open an application of **SURFACE** and load the data file designated as **FreeDrainingFurrow_2.cfg** and then open the input notebook by clicking on the input button ▦. Select the **Input Control** panel and click the "Continuous Inflow Hydrograph" radio button. Then simulate the system by clicking on the run button. The resulting in the advance/recession plot is shown in Figure III-11 and the tailwater hydrograph is shown in Figure III-12.

Except for the recession curve, the hydrograph data in the **FreeDrainingFurrow_2.cfg** data set are not simulated too well, and the intake parameters need to be adjusted. Actually, the hydrograph data were derived from different from a furrow of similar characteristics but different intake parameters. Note that the inflow for the hydrograph data is 0.033 cfs whereas the intake parameters in the data set were derived from an inflow of 0.022 cfs.

In order to calibrate the intake parameters using the volume balance procedure, click first on the **Infiltration Characteristics** panel and set the **Qinfilt** box to 0.033 cfs. Make sure the "Continuous Inflow Hydrograph" radio button in the **Input Control** is selected and that the parameters in the boxes below the Two-Point are set to 352.7 minutes, 116 minutes and 1013 feet respectively. Then click the Two-Point button and notice that the a and K parameters are adjusted to 0.2473 and 0.01859 respectively. Repeat the simulation using these data by clicking on the ▦ button. Finally, activate the advance/ recession and tailwater runoff hydrograph plots as presented below in Figs. III-13 and III-14.
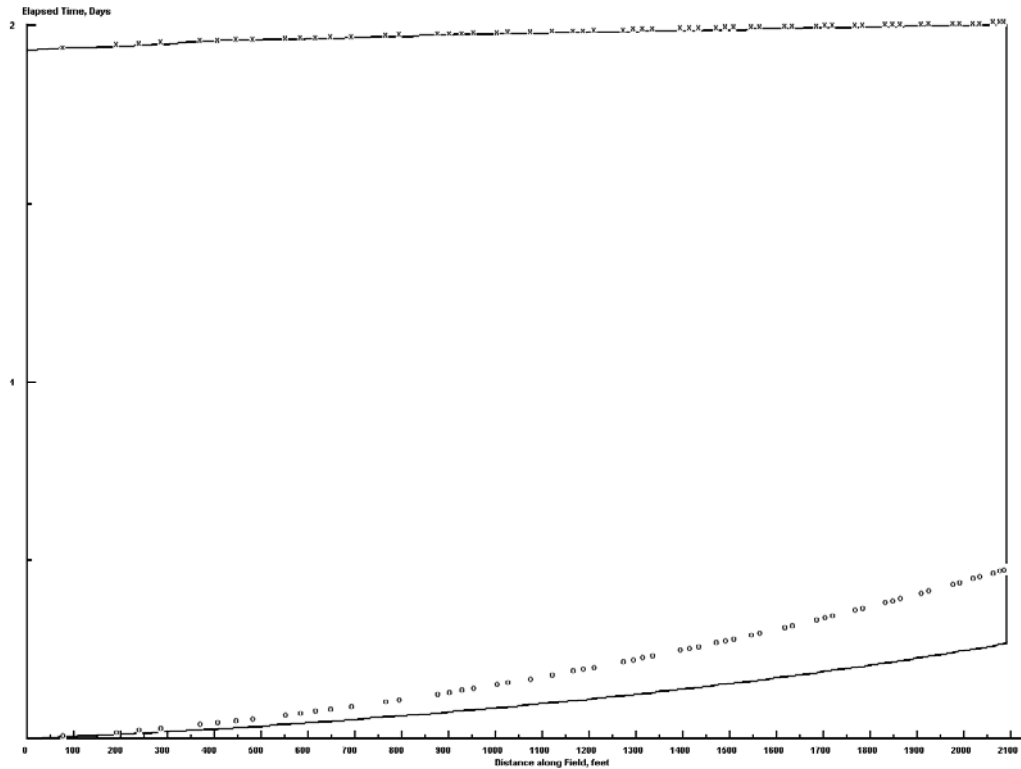
Figure III-11. Advance/recession curve for the example FreeDrainingFurrow_2.cfg data.
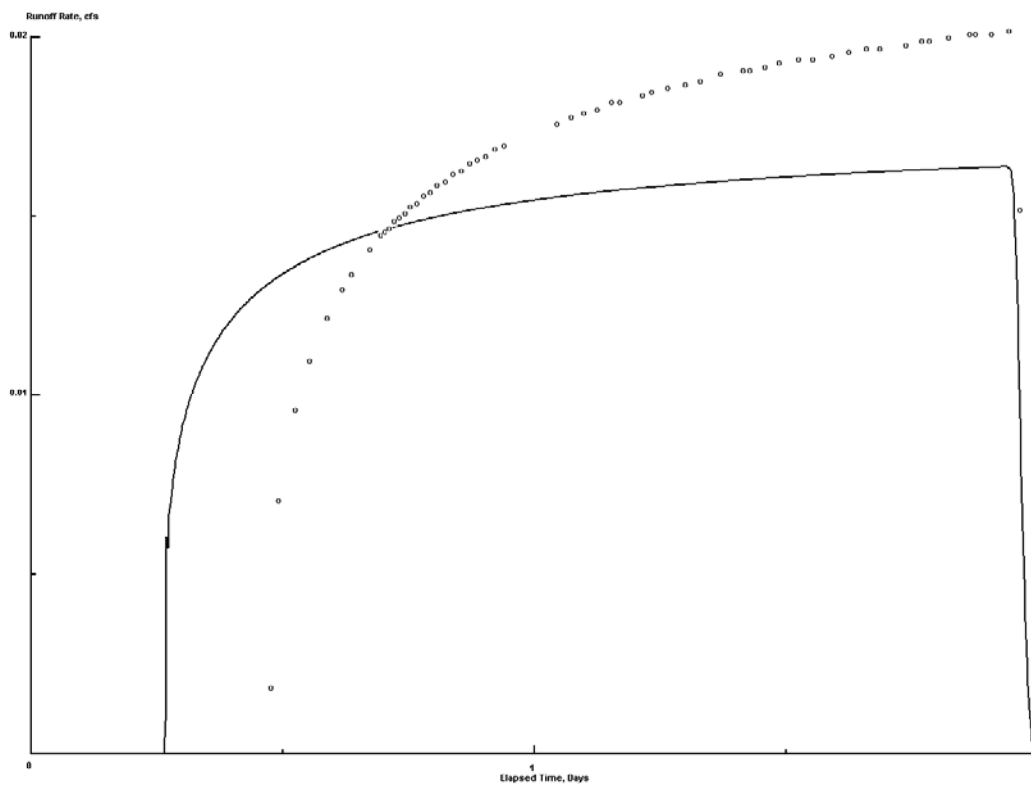
Figure III-12 Tailwater hydrograph for the example FreeDrainingFurrow_2.cfg data.
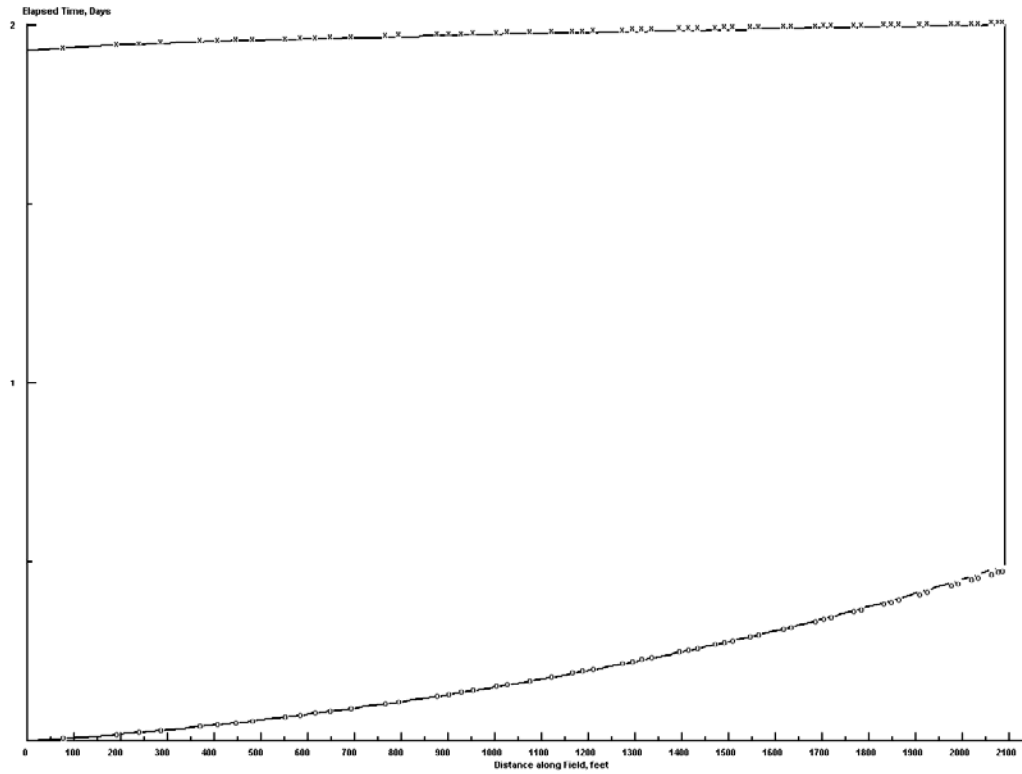
Figure III-13. Corrected advance/recession curve for FreeDrainingFurrow_2.cfg data.
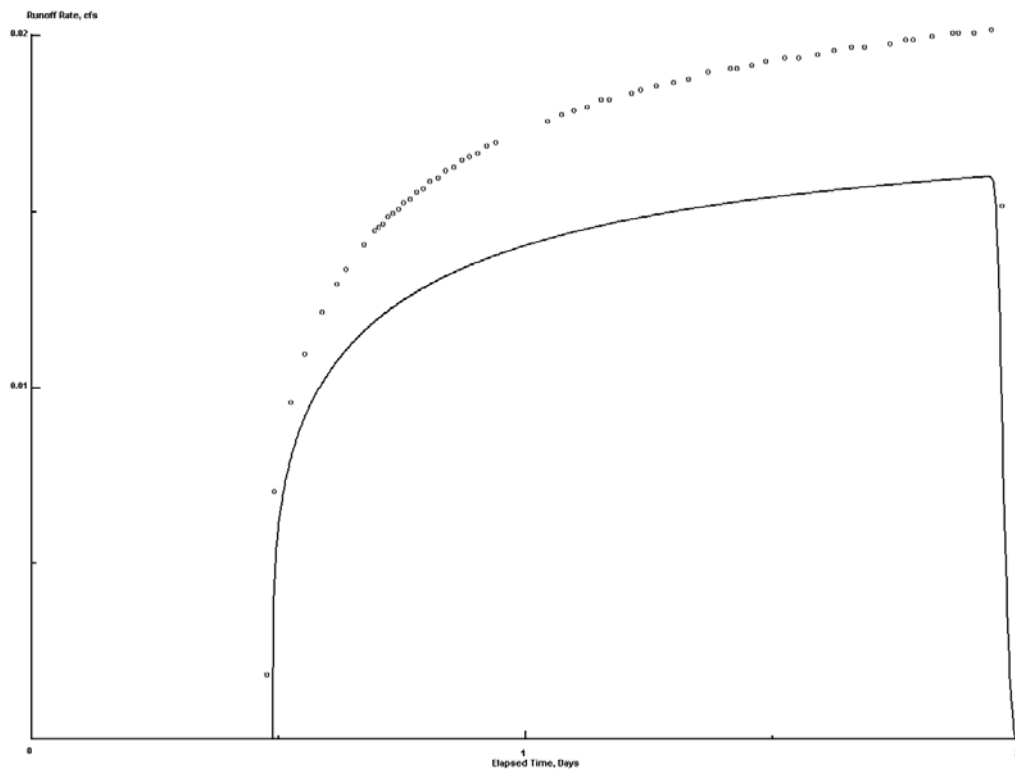
Figure III-14. Corrected tailwater hydrograph for FreeDrainingFurrow_2.cfg data.

The volume balance procedure calibrated the intake parameters so they produced an accurate simulation of the advance trajectory but under estimated the volume of tailwater indicating that the value of F_o is too large. To adjust the calibration so both the advance trajectory and the tailwater hydrograph are simulated accurately, reduce the value of F_o, by trial and erro, click on the Two-Point to adjust a and K with each F_o trial, and then re-run the simulation. When the value of F_o is about 0.00025 ft^3/ft/min, a is 0.3273, and K is 0.01432 ft^3/ft/min^a, the advance fit will appear like Fig. III-13 and the tailwater plot like Fig. III-15.
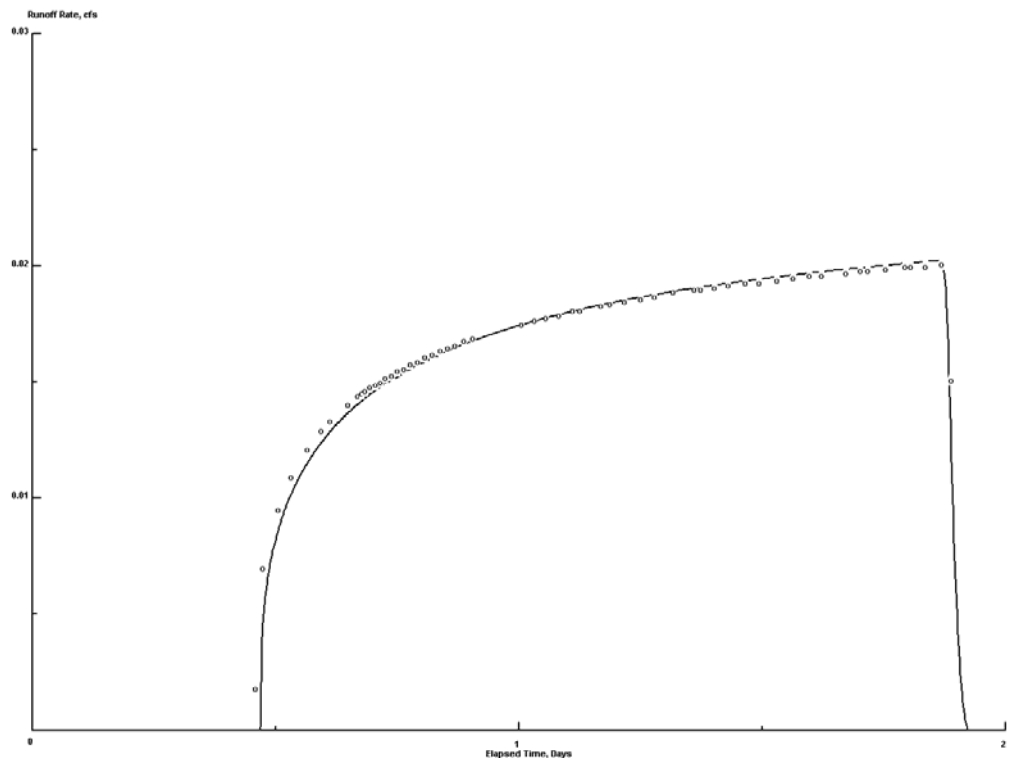
Figure III-15. Final simulated tailwater hydrograph for FreeDrainingFurrow_2.cfg data.

III.3.2.4 *Adjusting Infiltration for Furrow Wetted Perimeter*

Three situations exist that may require an adjustment of the infiltration parameters, a, k and f_o, or a, K, and F_o. The first is when values from Tables III.3 – III-6 need to be adjusted to distinguish between furrow and border/basin infiltration rates independently of Tables III-7 – III-10. The second case occurs where intake coefficients might be modified is where one wishes to delineate the effects of wetted perimeter variations along a furrow. The basic argument for not making this adjustment is that simultaneous adjustments must also account for varying roughness and cross-section, both of which tend to minimize the effect of wetted perimeter. And the third case occurs when the furrow infiltration coefficients have been defined using furrow advance data (and derived from one value of inflow, slope, length of run, etc.), but then the simulation or design analysis is based on a different values of field parameters. This is the most important of the three possible reasons for adjusting infiltration coefficients since improving simulation or design capabilities inherently implies field definition of infiltration.

The infiltration coefficients K, a and F_o in Tables III-3 – III-6 and Eq. III-14 are defined

for furrow irrigation at a specific discharge and therefore a specific wetted perimeter. If the simulated flow is significantly different from the discharge where infiltration is defined, the intake coefficients should be adjusted. Although there are a number of studies that have examined ways to adjust infiltration for wetted perimeter, most require a substantially more rigorous treatment of infiltration than can be accommodated here. Consequently, a relatively simple adjustment is used. Using From Eqs. III-27, III-28, and III.30, the wetted perimeter can be extracted and defined for the flow where the coefficients are determined:

$$WP_{Infilt} = \gamma_1 \sigma_1^{\frac{\gamma_2}{\sigma_2}} \left(\frac{\frac{0.4529 \cdot Q_{Infilt}^2}{3600} n^2}{S_o \rho_1} \right)^{\frac{\gamma_2}{\sigma_2 \rho_2}}$$

(III-56)

where Q_{infilt} is the flow where the infiltration coefficients have been determined in ft^3/min and WP_{Infilt} is the corresponding wetted perimeter in ft. Then the coefficient ξ is defined as:

$$\xi = \left[\frac{WP_o}{WP_{Infilt}} \right]$$

(III-57)

in which WP_o is the actual wetted perimeter at the field inlet. Then the Kostiakov-Lewis equation is revised by multiplying the K and F_o parameters by ξ:

$$Z = \xi \left[K\tau^a + F_o \tau \right]$$

(III-58)

III.3.2.5 General Comment

The adjustment of infiltration for wetted perimeter variation along the furrow is one topic of interest to model developers. It has generated some interesting debate. On one hand, the wetted perimeter is known to vary along the furrow with the decreasing flow and should be adjusted accordingly at each computational node. This concept is technically correct so far as discharge variation is concerned but relies also on the assumption that hydraulic roughness and cross-section are constant along the furrow, an assumption that is known to be weak. The other side of the argument is that two other important parameters are varying in a fashion that compensates for the diminishing discharge along the furrow. The roughness increases along the furrow as the effects of less water movement produces less smoothing of the furrow surface, thus increasing wetted perimeter. Also with less flow along the furrow the flow cross-section is less eroded and therefore less efficient. The result is that wetted perimeter remains nearly constant over a substantial length of furrow in spite of discharge reduction. This assumption was made in nearly all early versions of surface irrigation models. Report after report shows this to be adequate.

Another important issue in this regard is the spatial variability of infiltration and roughness. A number of studies have shown that measurements of roughness, K, a and F_o will exhibit a great deal of variation over a field. The analysis above assumes the values input will be representative of nearly average values for the field. Thus, while attempts have been made to adjust infiltration and roughness for the effects noted above, there are no provisions for spatial variation.

IV   Redesigning Surface Irrigation Systems

The vast majority of design efforts in the surface irrigation arena will be devoted to modifying or fine tuning systems already in place rather than the development of entirely new systems. Perhaps a more descriptive term would be "redesign". One can readily see different "design" objectives in the two views of surface irrigation design. The focus of "new system" design is to create a workable, profitable, and effective system. The focus of redesign or design modification is conservation of water, labor, soil, and capital resources.

The context of this section is redesigning surface irrigation systems for improving their performance. The term "design" will be used in the discussion and examples in order to be consistent with historical practice.

IV.1   THE OBJECTIVE AND SCOPE OF SURFACE IRRIGATION DESIGN

The surface irrigation system should replenish the root zone reservoir efficiently and uniformly so crop stress is avoided. It should provide a uniform and effective leaching application when needed. And occasionally, it may need to be capable of meeting special needs such as seed bed preparation, cooling, frost protection, and chemigation. It may also be used to soften the soil for better cultivation or even to fertilize the field and apply pesticides. Resources like energy, water, nutrients, and labor should be conserved.

The design procedures outlined in the following sections are based on a target application depth, z_{req}, which equals the soil moisture extracted by the crop between irrigations. The value of z_{req} is equivalent to the soil moisture deficit. Design is a trial and error procedure. A selection of lengths, slopes, field inflow rates and cutoff times can be made that will maximize efficiency and uniformity for a particular configuration. Iterating through various configurations provide the designer with information necessary to find a global optimum. Considerations such as erosion and water supply limitations will act as constraints on the design procedures. Many fields will require a subdivision to utilize the total flow available within a period of availability. This is a judgment that the designer must make after weighing all other factors that are relevant to the successful operation of the system. Maximum efficiencies, the implicit goal of design, will occur when the least-watered areas of the field receive a depth equivalent to z_{req}. Minimizing differences in intake opportunity time will minimize deep percolation and maximize uniformity. Surface runoff should be controlled or reused.

The design intake opportunity time is defined in the following way from Eqs. III-17 and III-18:

$$Z_{req} = K\tau_{req}^{a} + F_{o}\tau_{req} + C, \text{ for furrows}$$

$$\text{(IV-1)}$$

$$z_{req} = k\tau_{req}^{a} + f_{o}\tau_{req} + c, \text{ for borders and basins}$$

where Z_{req} is the required infiltrated volume per unit length and per unit width or per furrow spacing and τ_{req} is the design intake opportunity time. In the cases of border and basin irrigation Z_{req} is numerically equal to z_{req}. However for furrow irrigation the furrow spacing must be introduced to reconcile Z_{req} and z_{req} as follows:

$$\boldsymbol{Z_{req}} = z_{req}w \qquad\qquad\qquad\qquad (IV.2)$$

where w is the furrow to furrow spacing.

Whether the irrigation specialist is designing a new surface irrigation system or seeking to improve the performance of an existing system, the design should be based on careful evaluation of local soil, topography, cultural, and climatic conditions. The selection of system configurations for the project is in fact an integral part of the project planning process.

In either case, the data required fall into six general categories. These were noted in Section I and are provided here for emphasis.

1. the nature of irrigation water supply in terms of the annual allotment, method of delivery and charge for water, discharge and duration, frequency of use and the quality of the water;

2. the topography of the land with particular emphasis on major slopes, undulations, locations of water delivery and surface drainage outlets;

3. the physical and chemical characteristics of the soil, especially the infiltration characteristics, moisture-holding capacities, salinity and internal drainage;

4. the cropping pattern, its water requirements, and special considerations given to assure that the irrigation system is workable within the harvesting and cultivation schedule, germination period and the critical growth periods;

5. the marketing conditions in the area as well as the availability and skill of labor, maintenance and replacement services, funding for construction and operation, energy, fertilizers, seeds, pesticides, etc.; and

6. the cultural practices employed in the farming region especially where they may constrain a specific design or operation of the system.

IV.2 THE BASIC DESIGN PROCESS

The surface irrigation design process is a procedure to determine the most desirable frequency and depth of irrigation within the capacity and availability of the water supply. This process can be divided into a preliminary design stage and a detailed design stage.

IV.2.1 The Preliminary Design

The operation of the system should offer enough flexibility to supply water to the crop in variable amounts and schedules and thereby allow the irrigator some scope to manage soil moisture for maximum yields as well as water, labor and energy conservation, and changes in cropping patterns. Water may be supplied on a continuous or a rotational basis in which the flow rate and duration may be relatively fixed. In those cases, the flexibility in scheduling irrigation is limited by water availability or to what each farmer or group of farmers can mutually agree upon within their command areas. On-demand systems should have more flexibility than continuous or rotational water schedules and are driven by crop demands. During preliminary design the limits of the water supply in satisfying an optimal irrigation schedule should be evaluated. It is particularly important that water measurement be an integral component of the water supply and that it is capable of providing the appropriate depth of water to the field as indicated by Eq. III-24.

The next step in the design process involves collecting and analyzing local climate, soil and cropping patterns to estimate the crop water demands. From this analysis the amount of water the system should supply through the season can be estimated. Comparing the net crop demands with the capability of the water delivery system to supply water according to a variable schedule can produce a tentative schedule. Whichever criterion (crop demand or water availability) governs the operating policy at the farm level, the information provided at this stage will define the limitations of the timing and depth of irrigations during the growing season.

The type of surface irrigation system selected for the farm should be carefully planned. Furrow systems are favored in conditions of relatively high bi-directional slope, row crops, and small farm flows and applications. Border and basin systems are favored in the flatter lands, large field discharges and larger depths of application. A great deal of management can be applied where flexibility in frequency and depth are possible.

IV.2.2 Detailed Design

The detailed design process involves determining the slope of the field, the furrow, border or basin inflow discharge and duration, the location and sizing of headland structures and miscellaneous facilities; and the provision of surface drainage facilities either to collect tailwater for reuse or for disposal.

Land leveling can easily be the most expensive on-farm improvement made in preparation for irrigation. It is a prerequisite for the best performance of the surface system. Generally, the best land leveling strategy is to do as little as possible, i.e. to grade the field to a slope that involves minimum earth movement. Exceptions occur where other considerations dictate a change in the type of system, say, basin irrigation, and yield sufficient benefits to offset the added cost of land leveling.

If the field has a general slope in two directions, land leveling for a furrow irrigation system is usually based on a best-fit plane through the field elevations. This minimizes earth movement over the entire field, and unless the slopes in the direction normal to the expected water flow are very large, terracing and benching would not be necessary. A border must have a zero slope normal to the field water flow and thus will require terracing in all cases of cross slope. Thus, the border slope is usually the best-fit sub-plane or strip. Basins, of course, are level, i.e. no slope in either direction. Thus, terracing is required in both directions. When the basin is rectangular; its largest dimension should run along the field's smallest natural slope in order to minimize leveling costs.

Field length becomes a design variable at this stage and again there is a philosophy the designer must consider. In mechanized farming long rectangular fields are preferable to short square ones. This notion is based on the time required for implement turning and realignment.

The next step in detailed design is to reconcile the flows and times with the total flow and its duration allocated to the field from the water supply. On small fields, the total supply may provide a satisfactory coverage when used to irrigate the whole field simultaneously. However, the general situation is that fields must be broken into 'sets' and irrigated part by part, i.e. basin by basin, border-by-border, etc. These subdivisions or 'sets' must match the field and its water supply.

Once the field dimensions and flow parameters have been formulated, the surface irrigation system must be described structurally. To apply the water, pipes or ditches with

associated control elements must be sized for the field. If tailwater is permitted, means for removing these flows must be provided. Also, the designer should give attention to the operation of the system. Automation will be a key element of some systems.

The design algorithms herein utilized are programmed in the NRCS *SURFACE* software discussed in Section II. This section is intended to demonstrate the design and improvement processes.

IV.3 BASIC DESIGN COMPUTATIONS

The difference between an evaluation and a design is that data collected during an evaluation include inflows and outflows, flow geometry, length and slope of the field, soil moisture depletion and advance and recession rates. The infiltration characteristics of the field surface can then be deduced and the efficiency and uniformity determined for that specific evaluation. Design procedures, on the other hand, input infiltration functions (including their changes during the season and as flows change), flow geometry, field slope and length to compute advance and recession trajectories, the distribution of applied water, and tailwater volumes or pond. The design procedures also determine efficiencies and uniformities. However, the design process can be applied to many more field conditions than an evaluation to determine efficiencies and uniformities through of the surface irrigation model, NRCS *SURFACE*.

There are five basic surface irrigation design problems:

1. Free-draining systems;
2. Blocked-end systems;
3. Free-draining systems with cutback;
4. Free-draining systems with tailwater recovery and reuse; and
5. Surge flow systems.

The philosophy of design suggested here is to evaluate flow rates and cutoff times for the first irrigation following planting or cultivation when roughness and intake are at their maximums, as well as for the third or fourth irrigation when these conditions have been changed by previous irrigations. This will yield a design that will have the flexibility to respond to the varying conditions the irrigator will experience during the season. All of the specific data required for design were enumerated in Section II.

IV.3.1 Free Draining Surface Irrigation Design

All surface irrigation systems can be configured to allow tailwater runoff. However, this reduces application efficiency, may erode soil from the field, or cause similar problems associated with degraded water quality. It is therefore not a desirable surface irrigation configuration. However, where water is inexpensive the costs of preventing runoff or capturing and reusing it may not be economically justifiable to the irrigator. In addition, ponded water at the end of the field represents a serious hazard to production if the ponding occurs over sufficient time to damage the crop ("scalding").

Furrow irrigation systems normally allow the outflow of tailwater. Tailwater outflow from border systems is less common but remains a typical feature. As a rule, tailwater runoff is not a feature included in basin irrigation except as an emergency measure during high rainfall events or when the irrigators over-fill the basin. Thus, the design algorithms herein for free draining field conditions apply primarily to furrow and border systems.

The basic design procedures for free draining systems involve eight steps: (1) identify the "field control point"; (2) determine the required intake opportunity time (τ_{req}); (3) select a unit flow and compute the advance time (t_L); (4) compute the cutoff time; (5) evaluate uniformity and efficiency; (6) iterate steps 1 – 5 until the optimal system is determined, usually on the basis of maximum irrigation efficiency subject to a lower limit on storage efficiency; (7) repeat the design computation for the later irrigation conditions; (8) configure the field into sets that will accommodate the water supply, and (9) determine how to uniformly apply water using pipes, ditches, and controls.

At the end of this procedure, the designer should consider whether or not the field geometry should be changed, reducing the run length for example, or perhaps targeting a different application depth. Since the design computations can be made quickly, the designer should examine a number of alternatives before recommending one to the irrigator.

The location of the field control point is where the minimum application will occur. In free-draining furrows, this point is at the downstream end of the field. In borders the field control point may be at either end of the field depending on the recession processes and cannot be determined until the irrigation regime is simulated by the **SURFACE** software. The cutoff time is approximated by the sum of the required intake opportunity time, τ_{req}, and the advance time, t_L, for furrows. Recession can usually be neglected in furrow irrigation if the design computations are being made manually. For borders, the cutoff time is either of two conditions: (1) when the difference between the recession time ($\bar{t}_L$) and the advance time (t_L,) equals the required intake opportunity time (τ_{req}) for the case where the field control point is at the downstream end of the field; or (2) when the recession time at the field inlet (or depletion time, $\bar{t}_d$) equals the required intake opportunity time in the case where the field control point is at the field inlet.

There are volume balance procedures for accomplishing the free draining design process and they work reasonably well for furrow irrigation. They can be used for free draining borders but the recession computations are inaccurate. Consequently, it is not recommended that volume balance be used in design but rather the hydrodynamic features of the NRCS **SURFACE** software or a similar program such as the SRFR software.[9]

IV.3.1.1 *Example Free Draining FurrowDesign*

Open an instance of **SURFACE**, load the **FreeDrainingFurrow_1.cfg** data file supplied with the software, and execute the simulation programming, 🖩, for the initial intake condition. At the end of the simulation observe the distribution of infiltrated water and runoff as well as the various efficiencies and uniformity that were determined. Then click on the plot output

Simulated System Performance	
Advance Time, min.......	406.3
Application Efficiency, %....	47.51
Require'mt Efficiency, %....	99.29
Irrigation Efficiency....	52.62
Distribution Uniformity, %....	93.75
Dist. Efficiency, %....	47.94
Tailwater Fraction....	0.89
Deep Perc. Fraction....	51.60

[9] Strelkoff, T.S., Clemmens, A.J., and Schmidt, B.V. 1998. SRFR v. 3.31 -- Computer Program for Simulating Flow in Surface Irrigation: Furrows-Basins-Borders. U.S. Water Conservation Lab., USDA/ARS, 4331 E. Broadway, Phoenix, AZ 85040.

results, , and from the drop down menu ***Current Data Plot Options*** select ***Advance Data*** and then ***Tailwater Data.*** These two plots are reproduced here as Figures IV-1 and IV-2. The specific uniformity and efficiency terms associated with this irrigation are shown in the ***Simulated System Performance*** box in the lower right of the simulation screen.
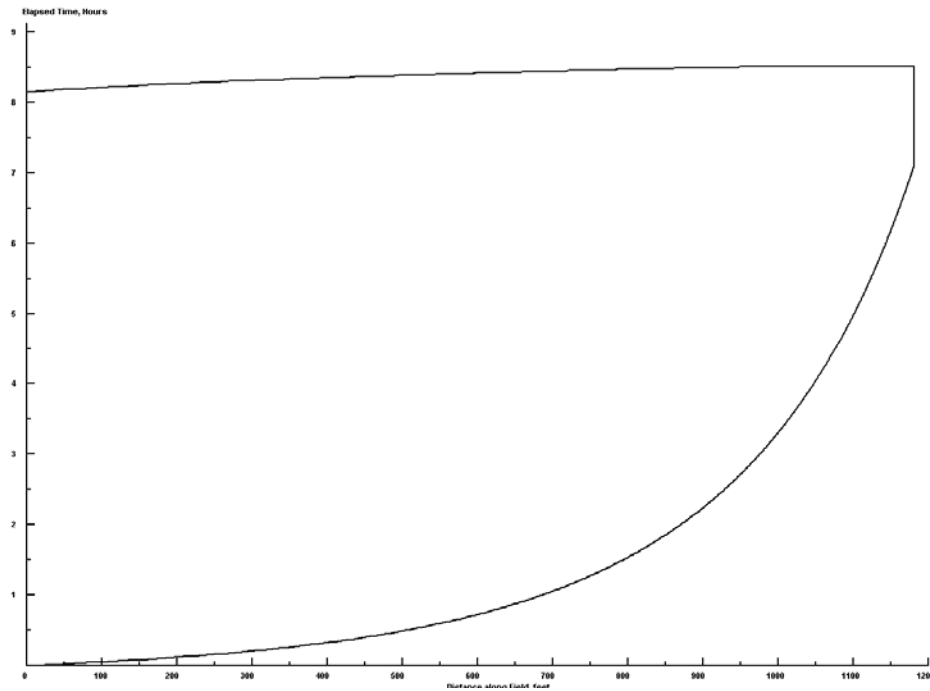
Figure IV-1. FreeDrainingFurrow_1 advance/recession trajectory.
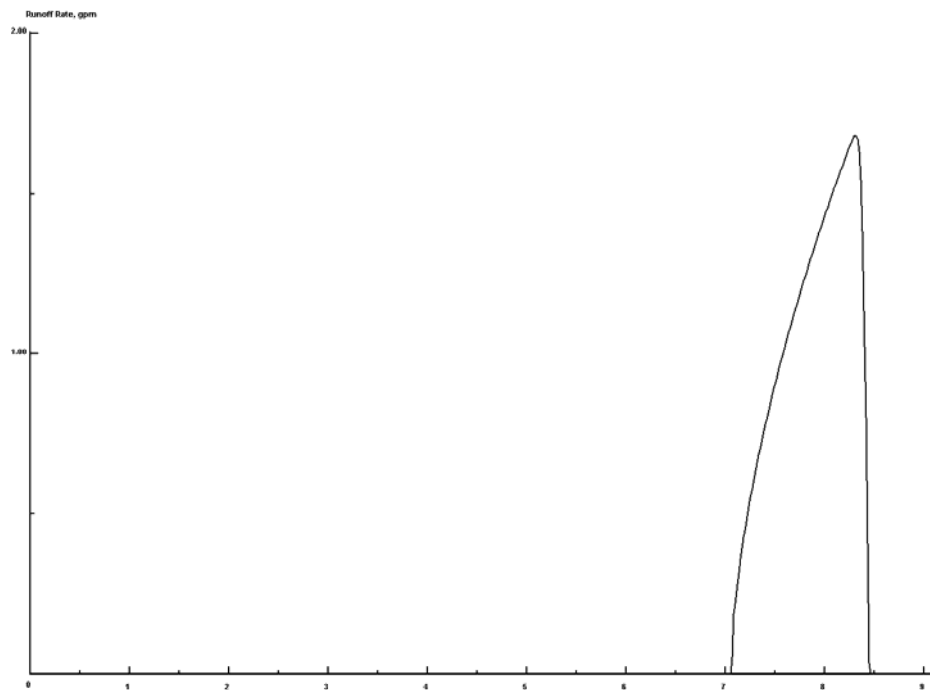
Figure IV-2. FreeDrainingFurrow_1 tailwater hydrograph.

The distribution of applied water from the main simulation screen is reproduced in Figure IV-3.
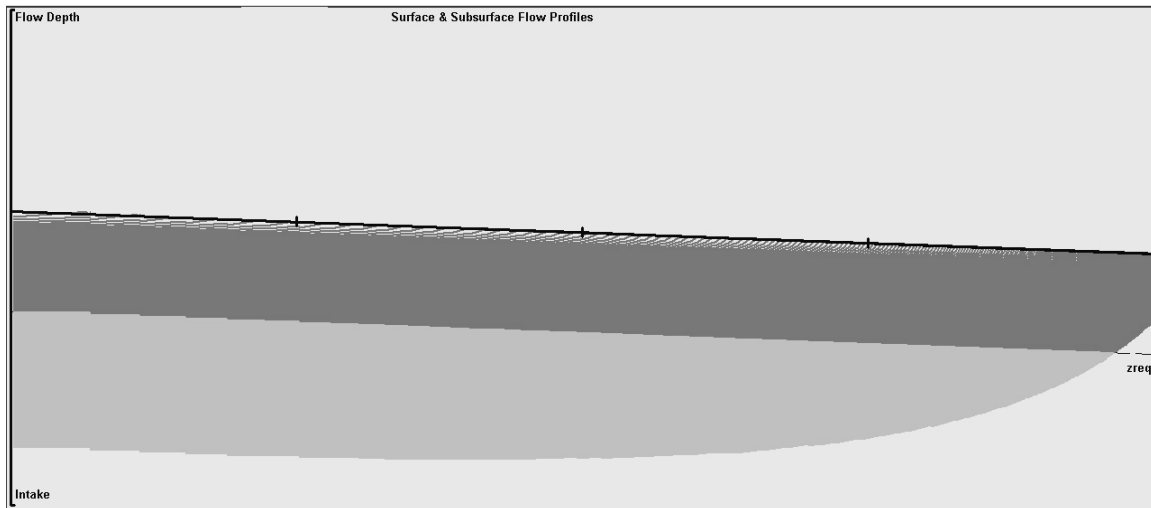
Figure IV-3. Soil moisture distribution from FreeDrainingFurrow_1 data.

Here is a classic case of a field that is too long for the soil intake characteristics. Even with a furrow stream of 32 gpm, the advance is not completed for almost seven hours. At the inlet where the intake opportunity time needed was only 160 minutes to apply the 4 inch depth required, the actual depth applied is almost 9.5 inches.

To begin examining alternatives to improve this irrigation, open the input tabbed notebook by clicking on the input button, ⬜. Then select the ***Design Panel***, shown in Figure IV-4.

Figure IV-4. SURFACE Design Panel for initial FreeDrainingFurrow_1 condition.

The first observation that can be made is the total flow required to irrigate the entire field simultaneously, shown in red is more than 30,000 gpm which is more than 12 times the flow available (2400 gpm). Click on the right field layout up-down button, ◄|►, until the conflict between available flow and required flow is resolved by irrigating in sets. Thirteen sets are required to satisfy the flow constraint but in doing so total time the supply needs to be available has increased to 104 hours whereas only 96 hours are allowed. Consequently, there does not appear to be a feasible design option irrigating the full length of these furrows. In cases where both time and flow constraints can be managed, the next step would be to determine if different flows and cutoff times would improve the irrigation.

Thus the next redesign option is to change the run length. This can be accomplished by clicking on the left up-down button, ▲▼, to cut the run length in half. Then the furrow stream size can be reduced along with changes in the time of cutoff to achieve a feasible and improved irrigation. Figure IV-5 is the design panel after a trial and error series of adjustments. Note that in order to satisfy the constraints on total available flow and duration, it has been necessary to divide the field into 18 sets, all of which are irrigated in 4-hours using a stream size of 22.5 gpm. The irrigation efficiency has been increased from about 47% to about 68%. The user may at this point wish to see if further improvements can be made.
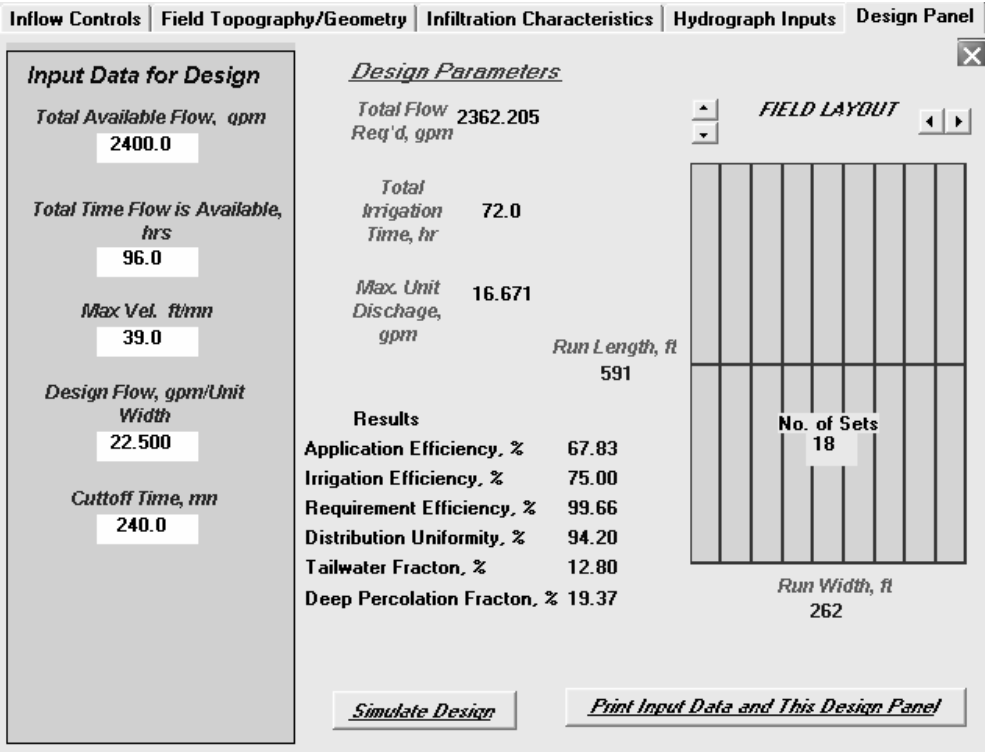

Figure IV-5. Improved design for initial irrigations.

Once the design has been made for the initial intake conditions it needs to be repeated for the later intake conditions. This can be accomplished by selecting the check box for the later irrigation conditions on the *Infiltration Characteristics* panel in the input tabbed notebook as shown in Fig. IV.6 and repeating the procedure noted above. The design for the later irrigations will be left to the reader to do, but as a hint, try reducing the number of sets to 9, increasing the cutoff time to 11 hours and reducing the furrow stream to 7.5 gpm.

Figure IV-6. Selecting the later irrigation conditions.

One of the most difficult aspects of surface irrigation is the reconciliation of the water supply characteristics and the on-field irrigation requirements. It can be observed that in the designs described above, the flow required was less than the total available. This assumes the supply flow rate is flexible. If the design processes are repeated with the delivery fixed at 2,400 gpm, the efficiency at the field level might be reduced considerably. In the case of the FreeDrainingFurrow_1 example, setting the **Design Flow** to 22.86 gpm for the initial irrigations reduces the irrigation efficiency by only one percent. The later irrigations in this case are not a serious problem. By reducing the unit flow to 7.62 gpm, it is possible to accommodate the entire 2,400 gpm supply and achieve about the same application efficiency of nearly 72%.

IV.3.1.2   *Example Free Draining Border Design*

In an open instance of **SURFACE**, load the **FreeDrainingBorder_4.cfg** and execute the simulation for the initial irrigation conditions. Figures IV-7 and IV-8 show the advance and recession trajectories and the tailwater hydrograph. The resulting soil moisture distribution shows that most of the border length was under-irrigated. The application efficiency is only 39%, primarily due to a 43% loss of tailwater. The 10% leaching fraction is more than satisfied with a nearly 17% deep percolation loss.

Both the unit discharge and the time of cutoff time are too large. By iteratively reducing the unit inflow and the duration of the irrigation it is possible to substantially improve the performance of this irrigation. In this case, it is not necessary to adjust the field length since the advance is relatively rapid. Figure IV-9 shows the design panel after several iterations. The irrigation efficiency has been improved to about 73% and the leaching requirement has been met on average although not uniformly. The irrigation set time has been decreased to 3 hours from the original 4 hours and the unit inflow has been reduced from 0.036 cfs/ft to 0.026 cfs/ft.
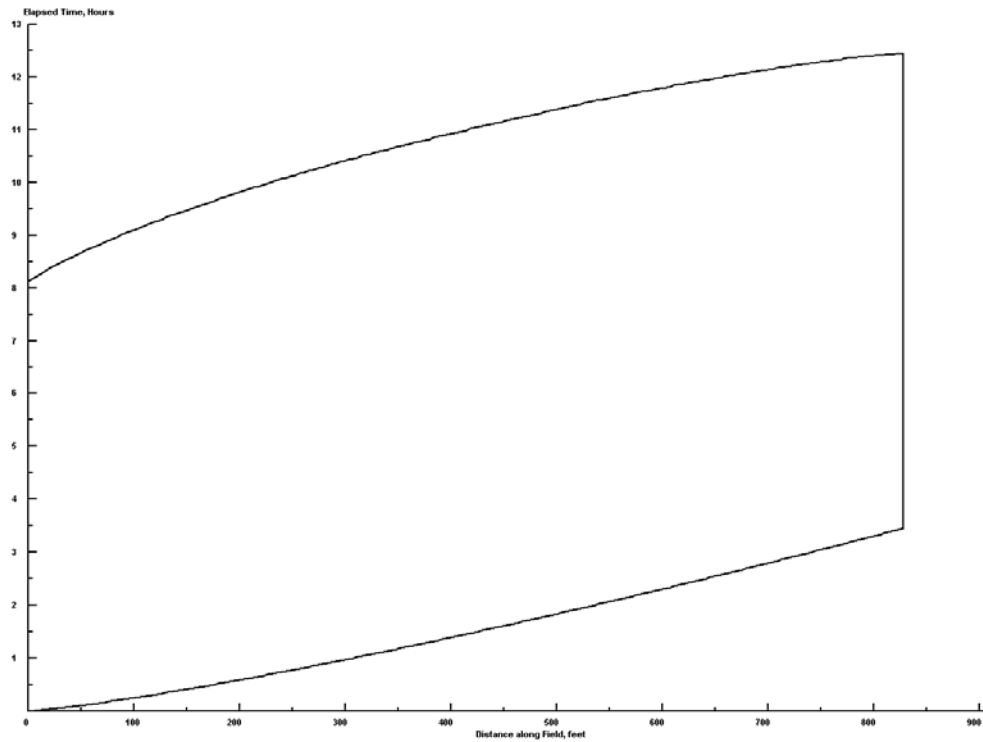
Figure IV-7. FreeDrainingBorder_4 advance and recession plots for initial irrigations.
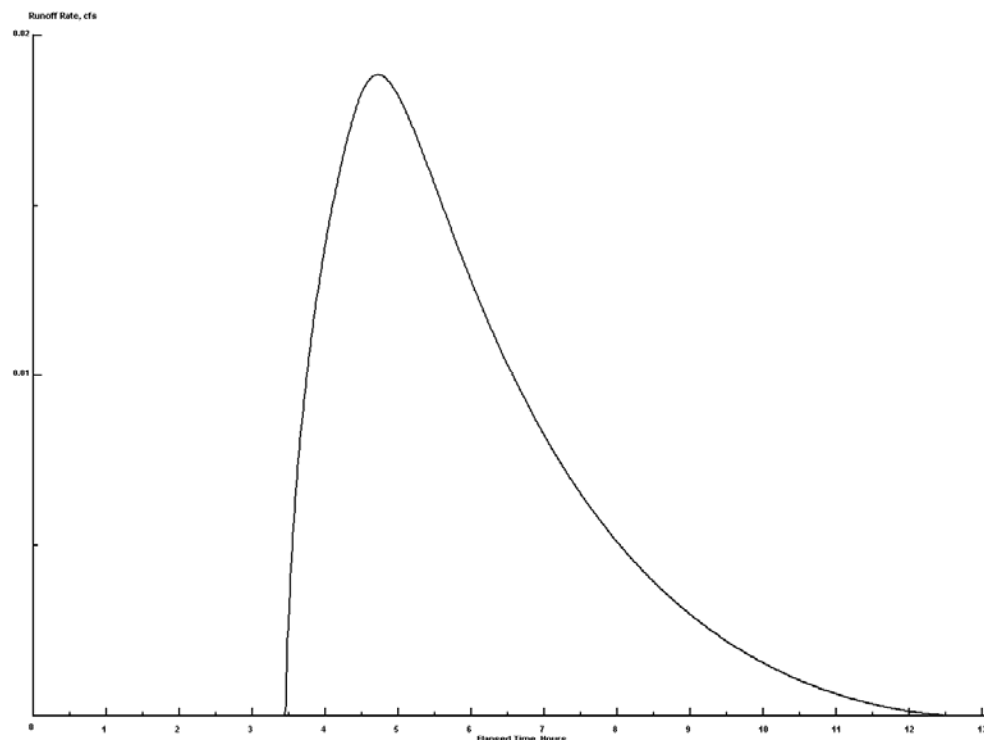
Figure IV-8. Tailwater hydrograph for FreeDrainingBorder_4 data.

Figure IV-9. Design Panel for the final design of the FreeDrainingBorder_4, initial irrigation example.

The design for the later intake conditions requires adjustments to the flow and cutoff time. By decreasing the flow to 0.01 cfs/ft and extending the cutoff time to 10 hours, the field can be irrigated in three sets achieving an application efficiency of 57%.

Although this irrigation example has been substantially improved, the performance is relatively poor and demonstrates two inherent problems with free draining borders. First, there can be as much as 5 times the amount of water on the field surface at the cutoff time as a furrow system and therefore tailwater can be a major problem. Secondly, if a substantial leaching requirement is needed high tailwater losses are unavoidable. The best performing borders, like basins, are those with blocked ends as will be demonstrated below.

The designer must now address the issue of whether or not the field has to accommodate the full 6 cfs during each irrigation, or whether it can be operated with a flexible supply flow. For the first irrigations, the field would need to irrigate with six sets each having a reduced flow of about 0.027 cfs/ft. The irrigation efficiency would decrease to 69% indicating that the efficiency "cost" would be about 4% due to fixing the field supply rate. Later irrigations would remain the same.

IV.3.2 Blocked-end Surface Irrigation Design

Blocking the end of basin, border, or furrow systems provides the designer and operator with the ability to achieve potential application efficiencies comparable with most sprinkle systems. While blocked-end fields have the potential for achieving high efficiencies, they also represent the highest risk to the grower. Even a small mistake in the cutoff time can result in substantial crop damage due to the scalding associated with prolonged ponding on the field.

Consequently, all blocked-end surface irrigation systems should be designed with emergency facilities to drain excess water from the field.

Figure IV-10 shows the four stages of typical blocked-end irrigation. In Fig. IV-10a water is being added to the field and is advancing. In Figure IV-10b, the inflow has been terminated and depletion has begun at the upstream end of the field while the flow at the downstream end continues to advance. This is important. Typical field practices for blocked-end surface irrigation systems generally terminate the inflow before the advance phase has been completed.

In Figure IV-10c, the depletion phase has ended at the upstream end, the advance phase has been completed, and the residual surface flows are ponding behind the downstream dike. Finally, in Figure IV-10d, the water ponded behind the field dike has infiltrated or been released and the resulting subsurface profile is uniform along the border and equal to the required or target application.

The dilemma for the designer of a blocked-end surface irrigation system is in determining the cutoff time. In practice, the cutoff decision is determined by where the advancing front has reached. This location may be highly variable because it depends on the infiltration characteristics of the soil, the surface roughness, the discharge at the inlet, the field slope and length, and the required depth of application. Until the development and verification of the zero-inertia or hydrodynamic simulation models, there were no reliable ways to predict the influence of these parameters or to test simple design and operational recommendations.

(a)

(b)

(c)

(d)
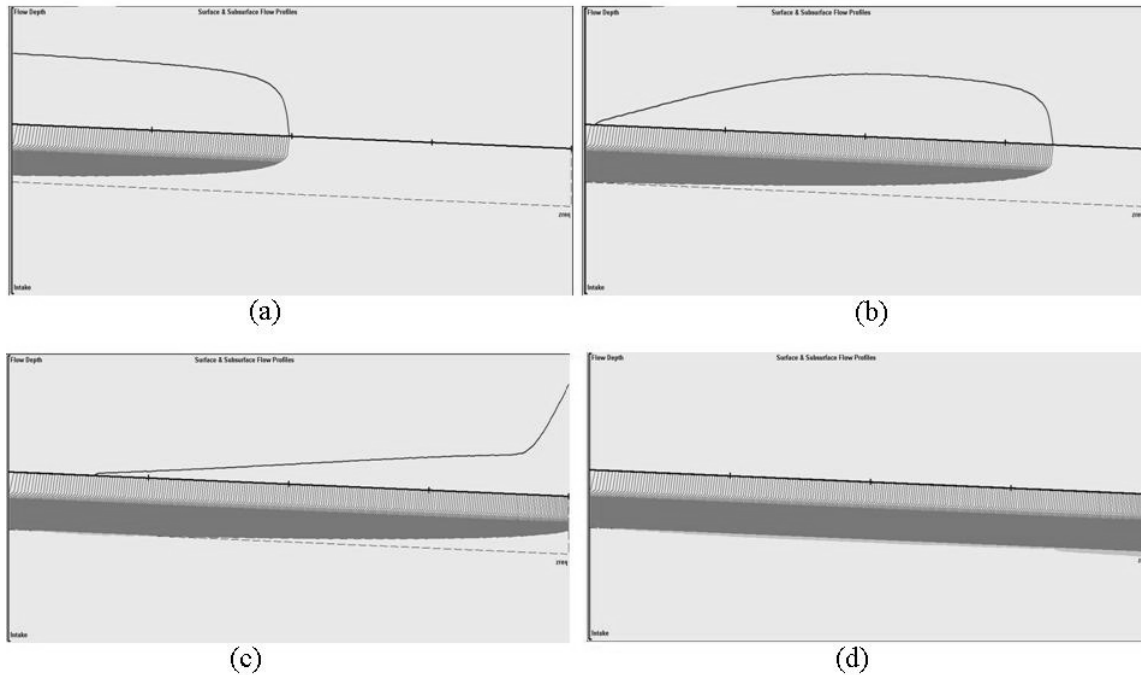
Figure IV-10. Stages of a blocked-end irrigation.

One simplified procedure for estimating the cutoff time is based on the assumption that the field control point is at the field inlet for blocked-end systems. By setting the field control point at the upstream end of the field, the cutoff time is approximated by the intake opportunity time, τ_{req} and is independent of the advance time, t_L. The specific cutoff time, t_{co}, may be

adjusted for depletion as follows:

$$t_{co} = \kappa \tau_{req} \qquad \text{(IV-3)}$$

where κ is a simple fraction that reduces t_{co} sufficiently to compensate for the depletion time. As a rule, κ would be 0.90 for light textured sandy and sandy loam soils, 0.95 for medium textured loam and silty loam soils, and 1.0 for clay and clay loam soils.

The volume of water the designer would like to apply to the field is as follows:

$$V_{req} = \psi \, z_{req} wL \qquad \text{(IV-4)}$$

in which the ψ is greater than 1.0 to allow for some deep percolation losses (leaching). If for instance the value of w is 1.0 foot and with L and z_{req} also in feet, then V_{req} is in ft^3. If a blocked-end system could apply V_{req} uniformly, it would also apply water with 100% application efficiency. Although a blocked-end system obviously cannot do so, the designer should seek a maximum value of efficiency and uniformity. Since Eq. IV-4 represents the best first approximation to that design, it is at least the starting point in the design process.

Given that the inflow will be terminated at t_{co}, the inflow rate must be the following to apply V_{req} to the field:

$$Q_o = \frac{V_{req}}{t_{co}} \qquad \text{(IV-5)}$$

The procedure for selecting t_{co} and Q_o for blocked-end systems given above is very simple yet surprisingly reliable. However, as one's intuition must surely warn, it cannot work in every case and needs to be checked by simulating the results with the **SURFACE** software. The risk with the simplified procedure is that some of the field will be under-irrigated and thus using Eq. IV-5 to select a flow rate rather than a more rigorous approach will be conservative.

IV.3.2.1   *Example Blocked End Border Design*

Open the file ***BlockedEndBorder.cfg*** and examine the input data. The target application depth is 3 inches and with the intake coefficients given will require an intake opportunity time of nearly 312 minutes for initial irrigations and 441 minutes for later irrigations. However, from the earlier simulation in which more than 26% of the inflow as deep percolation, the 3-inch application is probably too small. A more realistic value is 4 inches.

As a starting point, assume the values of κ and ψ in Eqs. IV-3 and IV-4 are 0.70 and 1.15 respectively. Accordingly, the times of cutoff can be estimated to the nearest on-half hour as 330 minutes and 420 minutes, respectively after rounding to the half-hour. From Eq. IV-4, the volume needed to replace the soil moisture depletion is 460 ft^3/ft so that from Eq. IV-5, the unit inflow should be 0.023 cfs/ft initially (460 ft^3/330 min/60 sec/min) and then 0.018 cfs/ft later. If these values are simulated in the **SURFACE** software, the results, shown in Figure IV-11, indicate an irrigation efficiency of more than 80% in both cases but the uniformity is poor near the end of the field. Succeeding iterations can be simulated by making small adjustments to the cutoff time and the inflow but these will produce only small improvements. Further improvements will require either shortening the run length or flattening the lower 25% of the

field to improve uniformity at the end of the field.
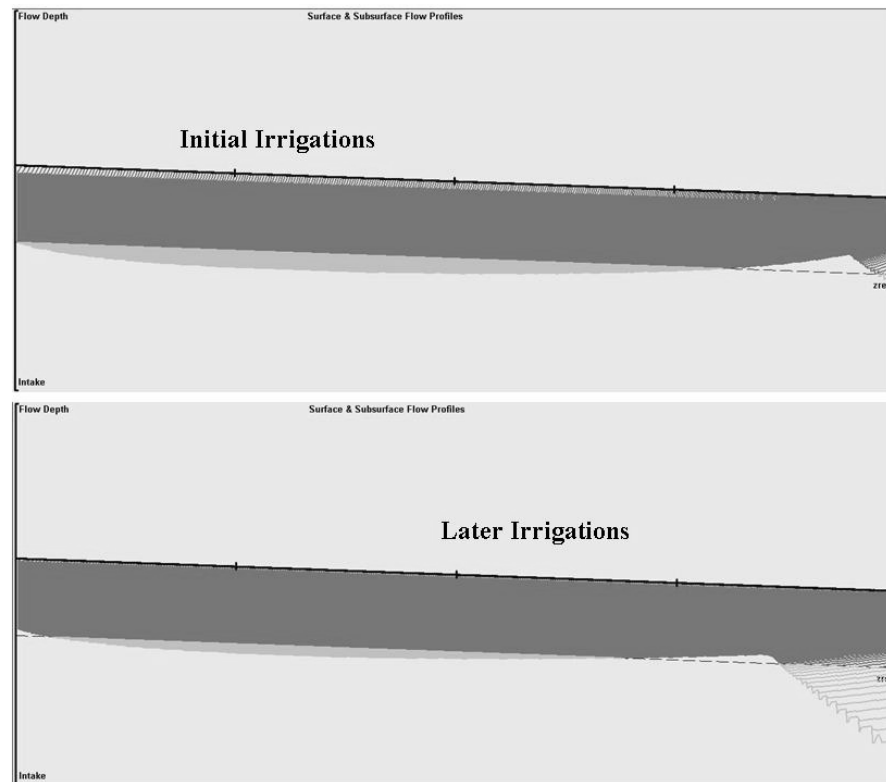
Figure IV-11. Simulation of the BlockedEndBorder data.

IV.3.3 Design Procedure for Cutback Systems

The concept of cutback has been around for a long time. A relatively high flow is used at the start of an irrigation to speed the advance phase along and then a reduced flow is implemented to minimize tailwater. As a practical matter however, cutback systems have never been very successful. They are rigid designs in the sense that they can only be applied to one field condition. Thus, for the condition they are designed for they are efficient but as the field conditions change between irrigations or from year to year, they can be very inefficient and even ineffective. One adaptation of the concept was the "Cablegation" system. Another was the development and adaptation of surge flow. Both have provided a flexible method of applying the cutback concept although the complexity of Cablegation is problematic.

The ***SURFACE*** software does allow one to simulate the conceptual cutback regime for both continuous and surge flow systems. Cutback irrigation involves a high continuous flow until the advance phase is nearing completion or has been completed, followed by a period of reduced or cutback inflow prior to the time of cutoff. The concept of cutback is more applicable to furrow irrigation systems than border systems and will thus be illustrated herein.

IV.3.3.1 *Example Furrow Cutback Design*

Run the ***SURFACE*** software with the ***CutbackDesing.cfg*** file loaded. Notice that the data file in the input tabbed notebook indicates the inflow regime has been defined by checking the ***Continuous Flow w/ Cutback*** box, and inputting 0.60 for the value of ***Cutback Ratio*** and 1.05 for

the **CB Length Fraction**. After looking at the data, click on the run button [image]. The simulated flow will complete the advance phase and then the inflow will be reduced resulting in the tailwater hydrograph shown in Fig. III-12.
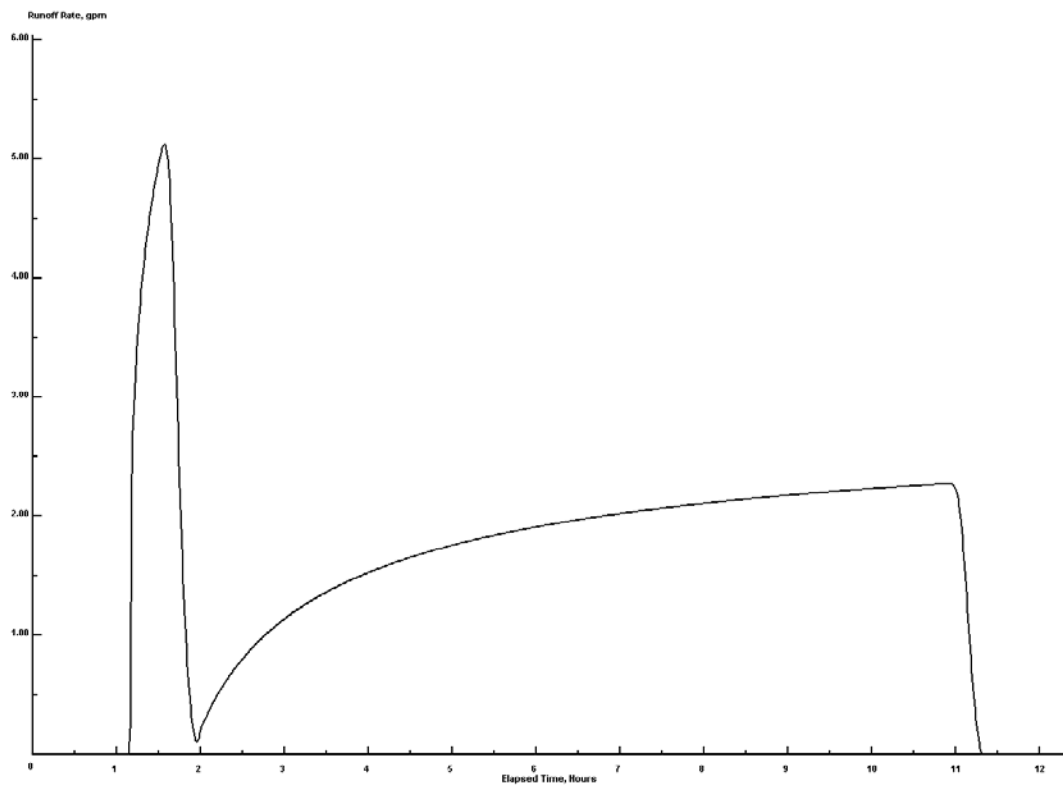
Figure IV-12. Simulated tailwater hydrograph using the CutbackDesign.cfg data file.

If the cutback ratio is too small, the reduced inflow wave will reach the end of the field and the downstream end of the field will dewater. For example set the cutback ratio to 0.50 and repeat the simulation. The version of the **SURFACE** software provided at the time of this manual cannot simulate this condition reliably. Consequently, an alert such as shown below will be presented on the screen as shown below and the simulation stopped. As instructed the user should adjust either the **Cutback Ratio** or the **CB Length Fraction** until the downstream does not dewater.

Nrcs_surface ✕

Cutback Dewatered the downstream end of the field. You will need to increase the value of the Cutback Ratio and/or increase the the Cutback Length Fraction.

OK

Nrcs_surface ✕

Solution Has Become Unstable. Check input data.

OK
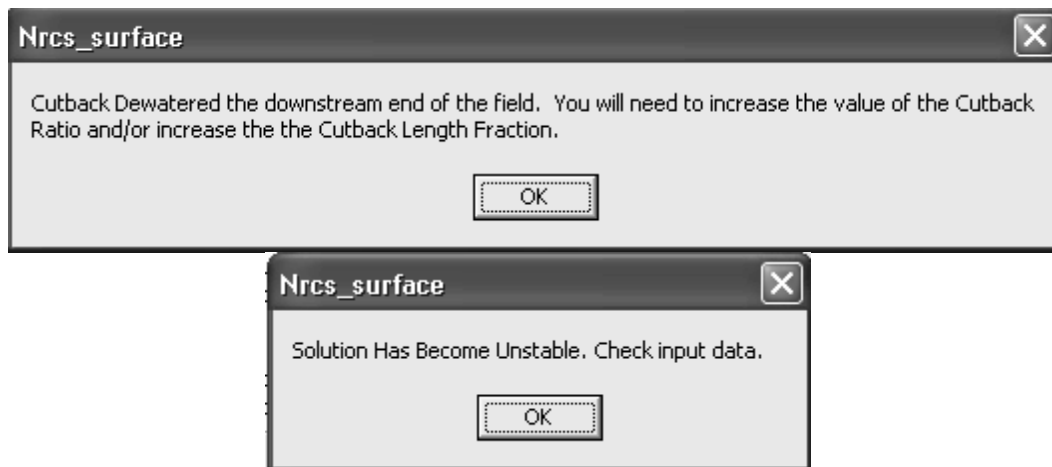
IV.3.4 Design of Systems with Tailwater Reuse

The efficiency of free-draining surface irrigation systems can be greatly improved when tailwater can be captured and reused. If the capture and reuse is to be applied to the field currently being irrigated, the tailwater reuse design is somewhat more complex than the procedure for traditional free-draining systems because of the need to utilize two sources of water. The major complexity of reuse systems is the strategy for re-circulating the tailwater. One alternative is to pump the tailwater back to the head of the field it originated from to irrigate some part of the field. Or, water captured from one field can be reused on another field. In any case, the tailwater reservoir and pumping system need to be carefully controlled and coordinated with the primary water supply.

Experience suggests that the costs of water from tailwater recycling can be as much as ten times the cost of water from an irrigation company or irrigation district. Further, the recycling system can be so difficult to manage and maintain that irrigators abandon them. To resolve these and related problems it is suggested that recycling be very simple, irrigate the field it originates from primarily, and not be mixed with the primary supply but rather irrigate a portion of the field independently.

To illustrate the design strategy for reuse systems, a manual design procedure for this simple configuration is first presented, and following, an example using the *SURFACE* software. A typical reuse system shown is schematically in Fig. IV-13 and is intended to capture tailwater from one part of the field and irrigate one of the sets.
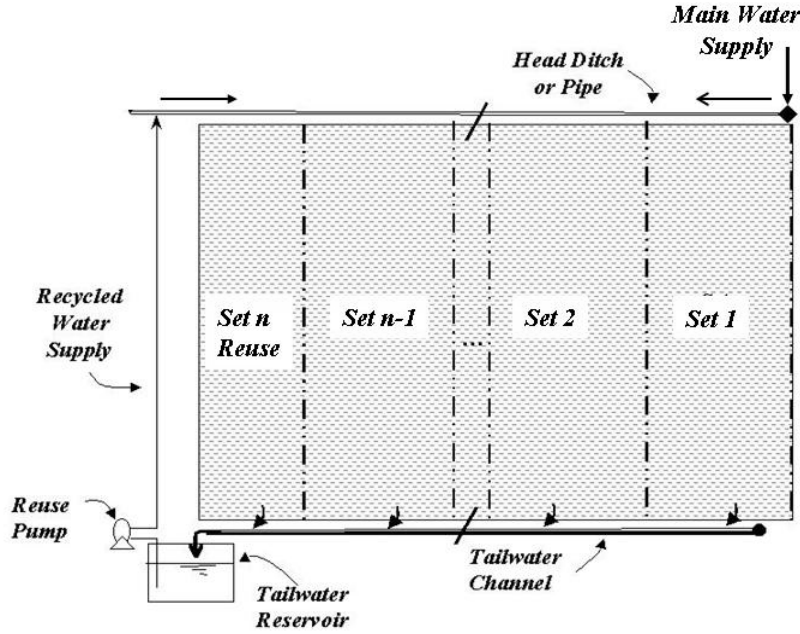
Figure IV-13. Schematic tailwater reuse system.

If the surface runoff is to be captured and utilized on another field, the reservoir would collect the runoff from the n sets of Fig. IV-13 and then supply the water to the headland facilities of the other field. This requires a larger tailwater reservoir but perhaps eliminates the need for the pump-back system.

In the simplest case of runoff reuse on an independent part of a field, the design is same whether the tailwater is collected and reused on the originating field or on another field. The procedure listed below deals with reuse on the originating field:

1. Compute the inflow discharge per unit width or per furrow and the time of cutoff for a free draining system that achieves as high an irrigation efficiency as possible without recycling. This discharge is a reasonable trade-off between the losses to deep percolation and tailwater and therefore will tend to minimize the size of the tailwater reservoir.

2. Evaluate the subdivision of the field into sets that will accommodate the total available flow and the duration of the supply.

3. Compute the total runoff volume per unit width or per furrow, V_{ro} from the originating field.

4. Compute the number of furrows or unit widths that can be irrigated from the recycled tailwater and the number that will be irrigated with the primary supply:

$$N_r = \frac{V_{ro} N_T}{\left(V_{ro} + Q_o t_{co}\right)}$$ (IV-6)

in which N_r is the number of unit widths or furrows that can be irrigated by the reuse system and N_T is the total unit widths or furrows in the field. And,

$$N_p = \frac{(F_w - N_r w)}{w} \tag{IV-7}$$

where F_w is the field width in feet, N_p is the number of furrow or unit widths to be irrigated by the main water supply and w is the unit width or furrow spacing in feet.

5. Steps 1 – 3 should then be repeated with an adjusted field width equal to the actual width, F_w, minus the width of the field to be irrigated with the recycled tailwater, $N_r w$.

6. The application efficiency, E_a, of this system is:

$$E_a = 100 \frac{z_{req} F_w L}{Q_o t_{co} N_p} \tag{IV-9}$$

7 The maximum volume of the tailwater reservoir would be equal to the total volume of recycled tailwater, $N_p Q_o t_{co}$ if the reuse system only operates after the primary supply has been shut off or directed to another field. A smaller reservoir is possible if the recycling can be initiated sometime during the irrigation of the main sets. Unless land is unavailable, the simplest system uses the maximum tailwater storage.

8. The tailwater during later irrigations may not be greater than during the initial irrigations. However, performing the design for both is since the capacity of the tailwater reservoir will be dictated by the maximum runoff.

IV.3.4.1 Example Furrow Tailwater Reuse Design

As an example of this procedure, consider the *FreeDrainingFurrow_2.cfg* data set. Following the procedure outlined above, the first step is to determine a flow and cutoff time that achieves as high of uniformity and efficiency as possible.

One of the better options is to simply reduce the inflow from 0.033 cfs per furrow to 0.023 cfs per furrow and leave the cutoff time and target depth as defined. This will reduce the tailwater fraction from about 40% to about 20%.

The volume balance within each furrow is computed in the performance box in the lower right hand side of the screen. From the design panel it can be observed that the field during this initial irrigation would need to be divided into three sets. Since the field is 2400 feet wide and the furrow spacing is 2.5 feet, the tailwater from the first set, and the size of the tailwater reservoir, would be,

Volume Balance in Cubic Feet			
Inflow	Outflow	Infilt	Error,%
1987.4	398.0	1584.8	0.23

$$\frac{2400 \ feet \ wide}{2.5 \ feet/furrow} \frac{1}{3 \ sets} \ 398 \ ft^3/furrow \ \frac{1 \, ac\text{-}ft}{43,560 \ ft^3} = 2.92 \, ac\text{-}ft.$$

From Eq. IV-6 the number of furrows that can be irrigated by reuse is,

$$N_r = \frac{V_{ro}N_T}{\left(V_{ro} + Q_o t_{co}\right)} = \frac{\dfrac{\left(398 \text{ ft}^3/\text{furrow}\right)\left(2400 \text{ ft}\right)}{2.5 \text{ ft} / \text{ furrow}}}{\left(398 \text{ ft}^3/\text{furrow} + .023 \text{ cfs} \cdot 60 \cdot 1440 \text{ mn}\right)} = 160 \text{ furrows}$$

The width of the field that should be irrigated by the main water supply is 2400-160 x 2.5 = 2000 feet. The value of 2,400 feet in the **Field Topography/Geometry** input panel needs to be replaced by 2,000 feet to reconfigure the field width. is made within the design panel as shown in Figure IV-14.

Computations now need to be repeated for the later irrigation conditions. After a few simulations it can be suggested that the target depth be decreased to 3 inches, the time of cutoff be increased to 30 hours (1,800 mn), the furrow stream reduced to about 4.5 gpm. This will result in a tailwater loss of about 123 ft³ per furrow and the field can be irrigated in two sets with the 10 cfs available. Following the same process as before, the number of furrows that can be supplied by the tailwater reuse system is 98. The reservoir volume would only need to be about 3.25 ac-ft for this condition as opposed to about 2.9 ac-ft for the initial irrigations.

IV.3.5 Design of Surge Flow Systems

A rational design procedure for surge flow systems has not been developed and thus is not included in the design features of the **SURFACE** software. This does not mean that design is not possible.   The simulation capabilities of the software can simulate any surge flow configuration, and through a trial and error process, a design can be derived that is efficient and effective.

Figure IV-14. FreeDrainingFurrow_2.cfg design of the field using the main water supply.

There are two critical design and operational rules for surge flow systems. First, the surges applied to the field during the advance phase should not coalesce, i.e., the advance front of one should not catch up and merge with a preceding surge. The second rule is that at the end of advance when cutback is desirable, the opposite should be facilitated – each surge should coalesce or merge.

The hydraulics of surges that do not coalesce behaves very much like the hydraulics of continuous flow at the same discharge, whereas the hydraulics of coalesced surges behaves very much like a cutback discharge. Thus, in the same irrigation management regime are the means to expedite rapid advance to minimize deep percolation as well as an effective way to implement cutback to minimize tailwater runoff during what some call the "soak cycle".

IV.3.5.1 *Example Surge Flow Design*

The *FreeDrainingFurrow_1.cfg* file was used in Section IV.3.1.1 to illustrate the problem of irrigating a long furrow in a relatively high intake soil. This is also one of the conditions that surge flow was originally thought to offer some advantage. If this file is loaded into the *SURFACE* software it can be modified to simulate various surge flow options. For purposes of example, the *Inflow Regime* in the *Inflow Control* panel of the input tabbed notebook can be

Simulated System Performance

Advance Time, min.......	21.8
Application Efficiency, %....	68.18
Require'mt Efficiency, %....	99.04
Irrigation Efficiency....	74.61
Distribution Uniformity, %....	84.49
Dist. Efficiency, %....	81.10
Tailwater Fraction....	15.94
Deep Perc. Fraction....	15.89

changed to a surge flow regime by checking on the box labeled "Fixed Cycle Surge Flow". Then under the headings of *Run Parameters* the number of surges can be set to a number like 7, and the "surge cycle on-time" to a value like 40 minutes. For the purposes of this demonstration, the furrow stream has left at 32 gpm but the target depth of application reduced to 3 inches. Also, the time step, *Dtm*, should be reduced to 0.5 minutes. Figure IV-15 shows the resulting advance/recession plot. The performance of the system is shown at the right. The implementation of surge flow in this case increased the application efficiency by only14% since the nearly 52% deep percolation loss and 1% tailwater loss under continuous flow became a 15% deep percolation loss and a 24% tailwater loss under the surge flow regime.

Another alternative is to use expanding cycles, for example if the *Variable Surge Flow* box is selected and a value of 15 minutes is entered into the *Surge Adj Time* box and the number of surges reduce to 4, the application efficiency can be increased another 6%.
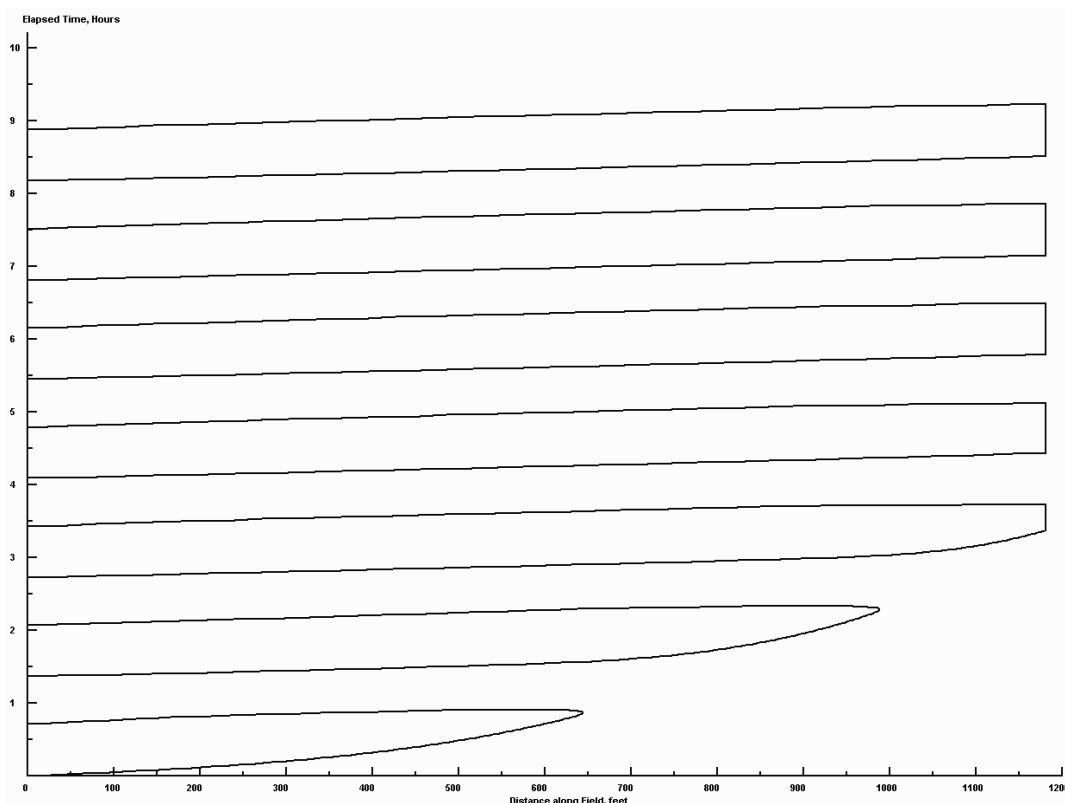
Figure IV-15. Surge flow advance and recession plot for FreeDrainingFurrow_1 example.

IV.4   HEADLAND FACILITIES

Water supplied to the surface irrigation system is distributed onto the field by various combinations of head ditches or pipelines equipped with outlets such as gates, siphons, spiles, and checks. Some of these are illustrated in Section I and are collectively known as headland facilities.

The design of surface irrigation headland facilities should satisfy three general criteria: (1) the water supply to the system must be distributed onto the field evenly; (2) the capacity of the headland facilities must be sufficient to accommodate the supply discharge; and (3) the headland facilities should prevent erosion as the flow emerges onto the field. It is not necessary for the individual outlets to be calibrated and capable of measuring flow but they should be adjustable enough to regulate the outlet flows.

IV.4.1 Head Ditch Design

A number of standards and manuals exist for the design of open channels and these should be reviewed in designing surface irrigation head ditches.[10][11]   This part of the National Engineering Handbook will not replace these documents but will present a few simple tools and guidelines for the design of head ditches.

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[10] USDA-NRCS. 1977. Design of Open Channels. Technical Release No. 25.
[11] USDA-NRCS. 1997. National Engineering Handbook, Part 652, Irrigation Guide.

Head ditches come in various configurations, lined and unlined, and equipped with different ways to divert water onto the field -- some of which are shown in Fig. IV-16. These can be designed so far as capacity is concerned with the "Manning Equation Calculator" found on the *Field Characteristics* panel of the input tabbed notebook of the *SURFACE* software.

There are three general criteria for effective head ditch design. The first is that flatter side slopes are better than steep ones. When the head ditch is diked-up to allow the diversion of water onto the field, ditches with flat side slopes have greater storage capacity at the higher ponded depths. Most small head ditches have slopes ranging between 1:1 to 1.5:1.

The second criterion for head ditch design is that the ditch capacity should carry the design flow at two-thirds of the ditch's constructed depth when it is not diked up for irrigation. This will allow offtakes such as spiles and ditch gates to be located above the water level in the areas of the field not being currently irrigated.

The third criterion is that the maximum depth in the ditch should not exceed 90% of the constructed depth. This criterion will come into focus as the ditch is diked to divert water onto the fields, and therefore, the design of offtakes should be such that the total flow can be diverted without exceeding the 90% limit. The remaining 10% of the ditch depth is freeboard and is necessary as a safety measure.

For example, in Section IV.3.2.1 --Blocked End Border Example, the flow required from the main supply was 10.0 cfs. If it is assumed that the head ditch is to be a trapezoidal concrete ditch running on the 0.0001 cross slope then the question is what the ditch dimensions should be. It should be kept in mind that only certain sizes of these ditches may be available from local contractors due to equipment limitations. For the purposes of this example, a ditch with a 3 foot depth, a 2-foot bottom width, a slope of 1.25:1, and a Manning n of 0.018, a typical value for concrete ditches, can be initially selected. Then using the "Manning Equation Calculator" in a trial and error manner a channel can be designed.

Flow Cross-Section	
Top Width (in)	114.000
Middle Width (in)	69.000
Bottom Width (in)	24.000
Maximum Depth (in)	36.000

Manning Equation Calculator	
Slope	0.00010
Manning n	0.0180
Flow, cfs	10.0001
Depth, ft	2.2362
Area, ft^2	10.8773
Top Width, ft	7.6787
Wetted Perimeter, ft	9.2533

As can be seen at the right, this ditch would carry the 10 cfs flow at a depth of 2.236 feet which is slightly more than the 2.0 feet specified under the two-thirds rule noted above. Increasing the bottom width to 30 inches would yield a depth of just over 2-feet. The maximum depth in the ditch should not exceed 90% of the depth, or 2.7 feet.

Furrow Ditch Gates

Furrow Siphons

Border/Basin Siphons

Border/Basin Check Outlet

Border/Basin Gate

Figure IV-16. Typical surface irrigation head ditch configurations.

This ditch is somewhat large due to the relatively flat cross slope of the field. It may be useful to construct the ditch on a steeper grade by elevating the inlet.

IV.4.1.1   *Sizing Siphon Tubes and Spiles*

Siphon tubes and spiles act as simple orfices. For the purpose of design, minor losses at their entrance and friction losses are assumed to be negligible. The design of these devices involves choosing a diameter that will accommodate the necessary flow. There are two conditions that typically exist in the operation of the siphons and spiles. The first is when the downstream end of the siphon or spile is submerged by the water level in the field as shown in Fig. IV-17b. The second condition occurs when the downstream end discharges freely into the air as shown in Figs. IV-17a and IV-17c. The head on these structures should be the typical difference between the operational level of the head ditch and either the field water level or the center line of the freely discharging spile or siphon. Table IV-1 provides guidelines for selecting siphon and spile diameters as a function of maximum discharge and head.

As an example, recall that in the example present in Section IV.3.1.1 a furrow flow of 22.5 gpm was suggested. From Table IV-1 it can be noted that when the head on the siphon or spile is about one foot or less, a 2-inch tube diameter should be selected. If the head is one foot or greater, the tube diameter can be reduced to 1.5 inches.

Another example using the information from Section IV-4-1 above is also illustrative. Suppose the diversion from the ditch is to be accomplished by siphon tubes and assume further the elevation of the water surface in the field is equal to the non-diked water elevation. The head on the siphons would therefore be the maximum water surface elevation in the ditch, at a depth of 2.7 feet, minus the field elevation of the field water surface, at a ditch depth of about 2 feet, or 0.7 feet, or about 8 inches. From Table IV-1 six-inch siphons would carry about 350 gpm and thus it would require 13 such siphons to divert the 10 cfs (4490 gpm) ditch flow. A better and less labor intensive solution would be either larger ditch gates or check outlets, both of which are discussed below.

IV.4.1.2   *Sizing Small Ditch Gates*

Small ditch gates as illustrated in Fig. IV-16 typically have round entrances and may be flush with the ditch side or recessed and vertical. The conduit through the ditch berm is also circular as a rule and submerged at the field side, making the offtake a submerged orifice. Commercial sizes from 2 inches to 24 inches are available. For 6-inch and smaller, the design is the same as for siphons and spiles detailed in Section IV.4.1.

IV.4.1.3   *Sizing Check Outlets and Large Ditch Gates*

A typical check outlet was shown in Fig. IV-16. They are usually equipped with simple slide inserts to close the opening when not in use although many check outlets are situated above the water level of the normal water flow in the ditch. These outlets normally operated at or near a free flow regime and therefore their flows are dependent only on the water level in the ditch. The head on these outlets is defined as the difference between the water elevation in the ditch and the elevation of the check crest.
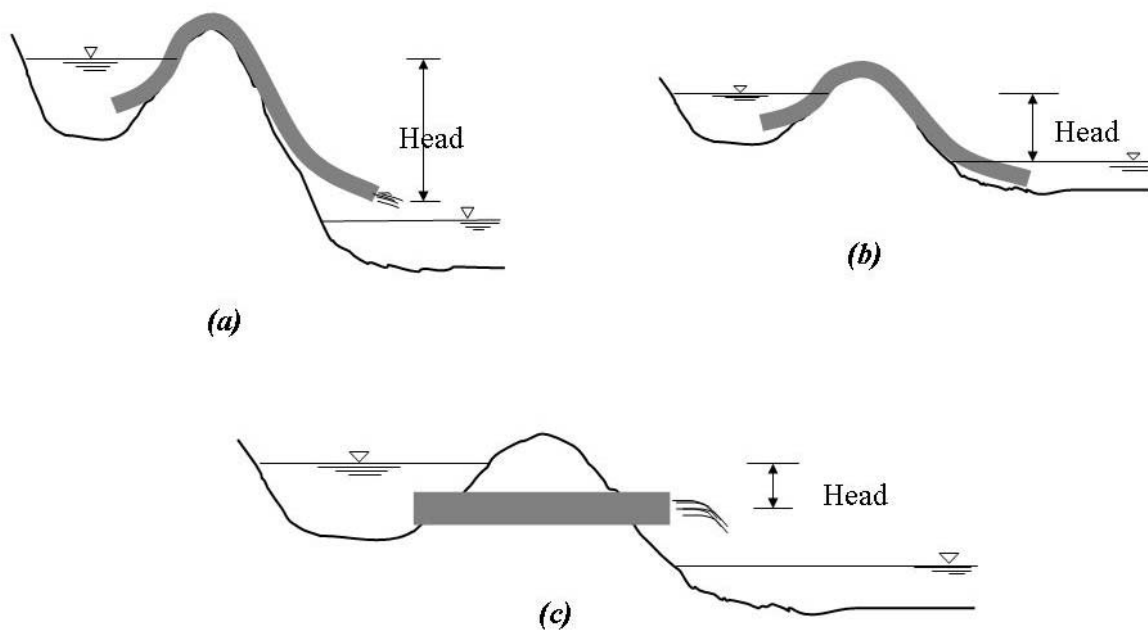
Figure IV-17. Typical operational conditions of surface irrigation siphons and spiles.

TABLE IV-1. MINIMUM RECOMMENDED SIPHON AND SPILE SIZES FOR SURFACE IRRIGATION SYSTEMS.

Table IV-2 gives the suggested minimum diameter gates for full open and completely submerged conditions (see Fig. IV-17b).

TABLE IV-2. MINIMUM RECOMMENDED DITCH GATE SIZES FOR SURFACE IRRIGATION SYSTEMS.

Head, inches	— Flow, gpm																																	
	0.5	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	4.0	4.5	5.0	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5
6																																		
8																																		
10																																		
12																																		24 Inch
15																																		
18																																		
24																																		
30																																		
36																																		
	6 inch				8 inch				10 inch		12 inch			15 inch						18 inch														
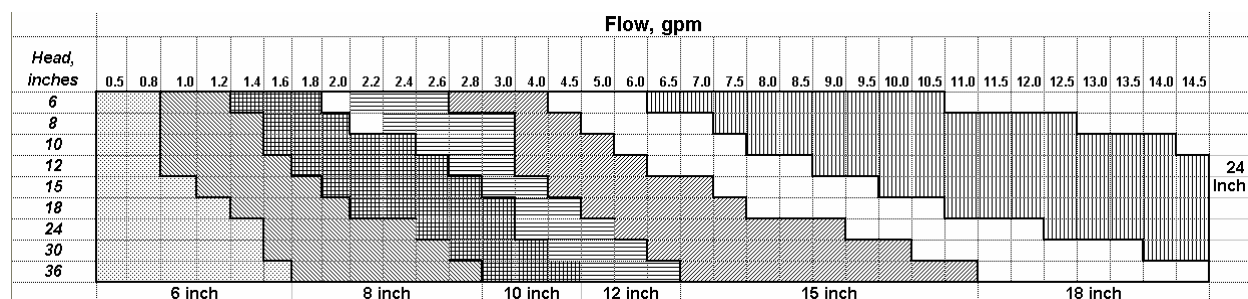
The sizing of large ditch gates like the border/basin gates illustrated in Figure IV-16 can be considered similarly to check outlets when at the maximum flow, the gate itself is raised above the water surface (specifically as illustrated in Figure IV-16). Unlike small ditch gates, the large gates are almost always rectangular in shape.
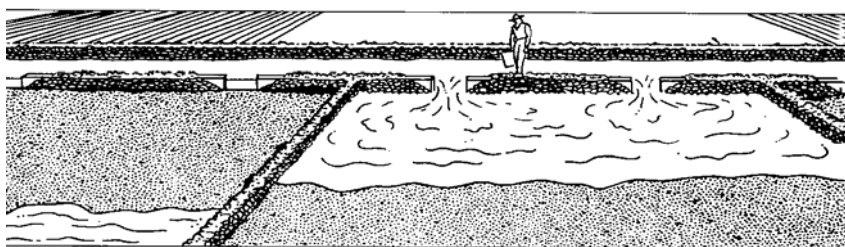
Table IV-3 gives the sizing of check outlets and large ditch gates.

TABLE IV-3. MINIMUM RECOMMENDED CHECK OUTLET AND LARGE DITCH GATE SIZES FOR SURFACE IRRIGATION SYSTEMS.

Head, inches	— Flow, cfs																										
	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0	9.0	10.0	12.0	14.0	16.0	18.0	20.0	25.0	30.0
6																											
8																											
10																											
12																											
15																											
18																											
24																											
Opening Width	1 foot																				2 feet					3 feet	4 feet
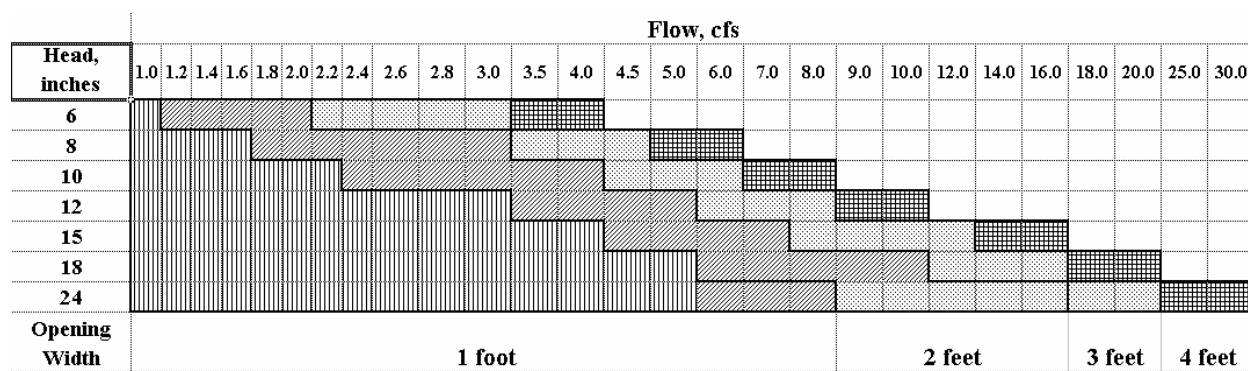
IV.4.2 Gated Pipe Design

Gated pipe is generally used for furrow irrigation, although in some cases it has been used for border and basin systems. Usually, borders and basins require larger flows than would normally be available through gated pipe systems. Gated pipe is available in aluminum, rigid plastic (polyvinyl), and lay flat (polypipe) from various manufacturers. Aluminum pipe is available in 5-inch, 6-inch, 8-inch, 10-inch, and 12-inch diameters. Polyvinyl gate pipe is usually available in 6-inch, 8-inch, 10-inch, and 12-inch. Lay flat is available in the same sizes as well as 9-inch, 15-inch 16-inch, 18-inch, and 22-inch.

The design of gated pipe involves three steps: (1) choosing a pipe material; (2) selection and location of the gated outlets; and (3) the selection of the pipe size.

IV.4.2.1   *Choosing a Pipe Material*

In selecting a particular type of irrigation gated pipe, irrigators must balance their needs against the cost, availability, operation, and maintenance of aluminum, rigid plastic, and lay flat pipe.

Aluminum gated irrigation pipe has been used the longest for furrow irrigation. It is the most expensive gated pipe but one that has the longest useful life (10-15 years) when proper maintenance is applied. Aluminum gated pipe typically costs about 50% more than polyvinyl and three times as much as the lay flat gated pipe. It is easy to move and install, and since it is supplied in 20, 30, or 40 foot lengths it is easy to store and clean. One of the disadvantages of aluminum gated pipe aside from its high initial cost, is the leakage from the pipe joints when maintenance is not adequate. Once the gates are installed the flexibility of alternative furrow spacing is reduced as well. The sizes of aluminum pipe are somewhat restricted with the most generally available sizes being 6, 8, 10, and 12 inch diameters.

Polyvinyl gated pipe is rigid like the aluminum pipe, easy to install and maintain, but will not be as rugged as aluminum and therefore should not have the expected life. It does however have a lower initial costs and a wider range of sizes. Polyvinyl gated pipe can be obtained for same size of pipe as aluminum but for 15 and 18-inch sizes on special order.

Lay-flat plastic gated pipe has become very popular in many locations in recent years. Its initial cost is low and it may only be useable for one or two seasons. It is the disposable alternative to aluminum and polyvinyl pipe. It also comes in wide range of sizes, 5-22 inches in diameter and is provided in rolls of several hundred feet rather than the 20-40-foot lengths of the rigid pipe. It is thus easier to install and remove. On the other hand it is more susceptible to tears and punctures and it is very difficult to remove sediments from the pipe due to its length. The offtakes can be installed in the field with simple tools and then replaced with inexpensive plugs if the spacing needs to be changed for other crops. Thus, the lay-flat gated pipe is the most flexible in terms of use. Lay-flat tubing has two additional disadvantages. First, the pressure head that it can accommodate is substantially below the value for the rigid pipes, and second, it is generally necessary to prevent the pipe from moving between irrigations due to wind.

IV.4.2.2   *Gated Outlets*

There are several gates used in gated pipe. They range from slide gates to simple plugs and the discharge characteristics depend on their size and shape. A typical head discharge curve for fully-open slide gates is shown in Fig. IV-18 and is presented for general guidance. In design practice, it will be necessary to know the specific characteristics of the gate actually used in the pipe. Figure IV-18 is intended to be an approximate tool that can be used to size the gated pipe itself.

General Head-Discharge Relation for Gated Pipe Outlets
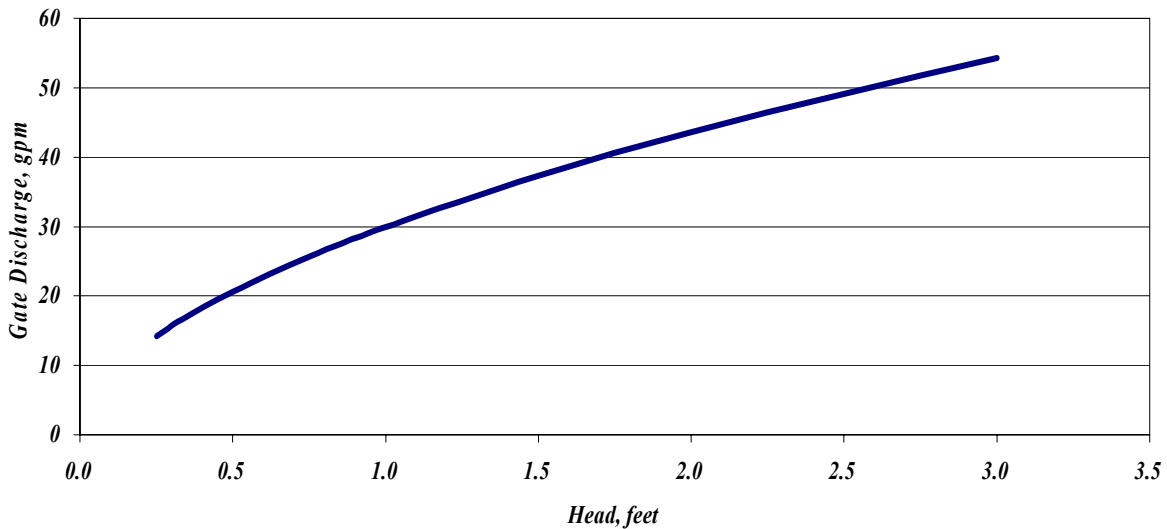
Figure IV-18. Typical head-discharge curve for gated pipe outlets.

It should also be noted that preceding any design of the headland facilities, the design of the field system must be completed so the unit flows and times of cutoff are known. Then from Figure IV-18 the operating head on the fully open gate can be determined which corresponds to the design unit flow (furrow flow). This is the minimum design head in the gated pipe. The flow from gates closer to the inlet end of the pipe will require regulation by adjusting the gate opening. Finally, gates should be spaced along the pipe at the same distance as the furrow spacing even when alternate furrows are irrigated.

IV.4.2.3   Gated Pipe Sizing

The design of gated pipe relies on several pieces of information. From the field design the unit or furrow discharges are known along with the total flow available to the field. The water supply to the field should also be characterized by its energy or head at the field inlet. This information may need to be developed from the elevation of the water source if coming from a canal or ditch, or from the pressure in the main supply pipeline if otherwise. If the field cannot be irrigated in a single set, its subdivisions should also be known. This information will establish the length of gated pipe segments. Finally, the field topography should yield the slope along which the gated pipe will be laid.

For purposes of design, the discharge in the gated pipe will be assumed to be the total field supply flow even though where the outlets are opens the flow diminishes along the pipe. This assumption is made to insure an adequate pipe diameter in the reaches which are simply conveying water to the irrigating location. The hydraulics of the pipe are thus described by the "Bernouli" equation:

$$H_{inlet} = h_f L/100 + \left(EL_{end} - EL_{inlet} \right) + H_{min} \qquad\qquad \text{(IV-10)}$$

in which, H_{inlet} = the total head (pressure plus velocity) at the inlet end of the gated pipe, in feet;

$$H_{min} = \quad \text{the minimum head at the end of the pipe necessary to deliver the}$$
design unit flow, in feet;

L $=$ length of the gated pipe, in feet;

EL_{end} $=$ elevation of the end of the gated pipe, in feet;

EL_{inlet} $=$ elevation of the pipe inlet, in feet; and

h_f $=$ the friction gradient in the pipe, in feet/100 feet.

Equation IV-10 can be solved for h_f as follows:

$$h_f = \frac{H_{inlet} - (EL_{end} - EL_{inlet}) - H_{min}}{L/100} \qquad \text{(IV-11)}$$

Then with a computed value of h_f, the designer can select the proper pipe diameter from Table IV-4.

TABLE IV-4. MINIMUM RECOMMENDED GATED PIPE DIAMETERS FOR VARIOUS FRICTION GRADIENTS.

Head Loss, ft/100 ft	Flow, gpm																							
	100	200	300	400	500	600	700	800	900	1000	1200	1400	1600	1800	2000	2200	2400	2600	2800	3000	3200	3400	3600
0.01																							
0.01																							
0.02																							
0.03																							
0.04																							
0.05																							
0.06																							
0.07																							
0.08																							
0.09																							
0.10																							
0.15																							
0.20																						22 inch	
0.25																							
0.50																						18 in	
0.75																							
1.00																							
1.25																							
1.50																						16 inch	
1.75																							
2.00																							
2.25																							
2.50																							
2.75																							
3.00																							
3.25																							
3.50																							
4.00																							
Gate Pipe Diamter	6 inch					8 inch				10 inch					12 inch								

IV.4.2.4   *Example Gated Pipe Design*

In the example give in Section IV.3.1., "FreeDrainingFurrow_1 Example", the field was 1,180 feet long and 2,362 feet wide. The field design for initial irrigations called for eighteen sets to be organized by subdividing the length into two parts and the width into nine parts (see Fig. IV-5). The cross-slope was 0.0001. The design furrow flow was 22.5 gpm and the total flow is 2,362 gpm.

Suppose this field is to be irrigated by a gated pipe system supplied by a buried pipe mainline as shown in Figure IV-19 in which the basic supply enters the field in a 1,500 foot pipe from the upper left hand corner, traverses to the middle of the field width, then turns 90° and extends to the mid point of the field length. The supply pipe connects to a canal offtake in which the water elevation is 15 feet higher than the 90° turn. Optimally, the pressure head at the 90° turn should be 6 feet.
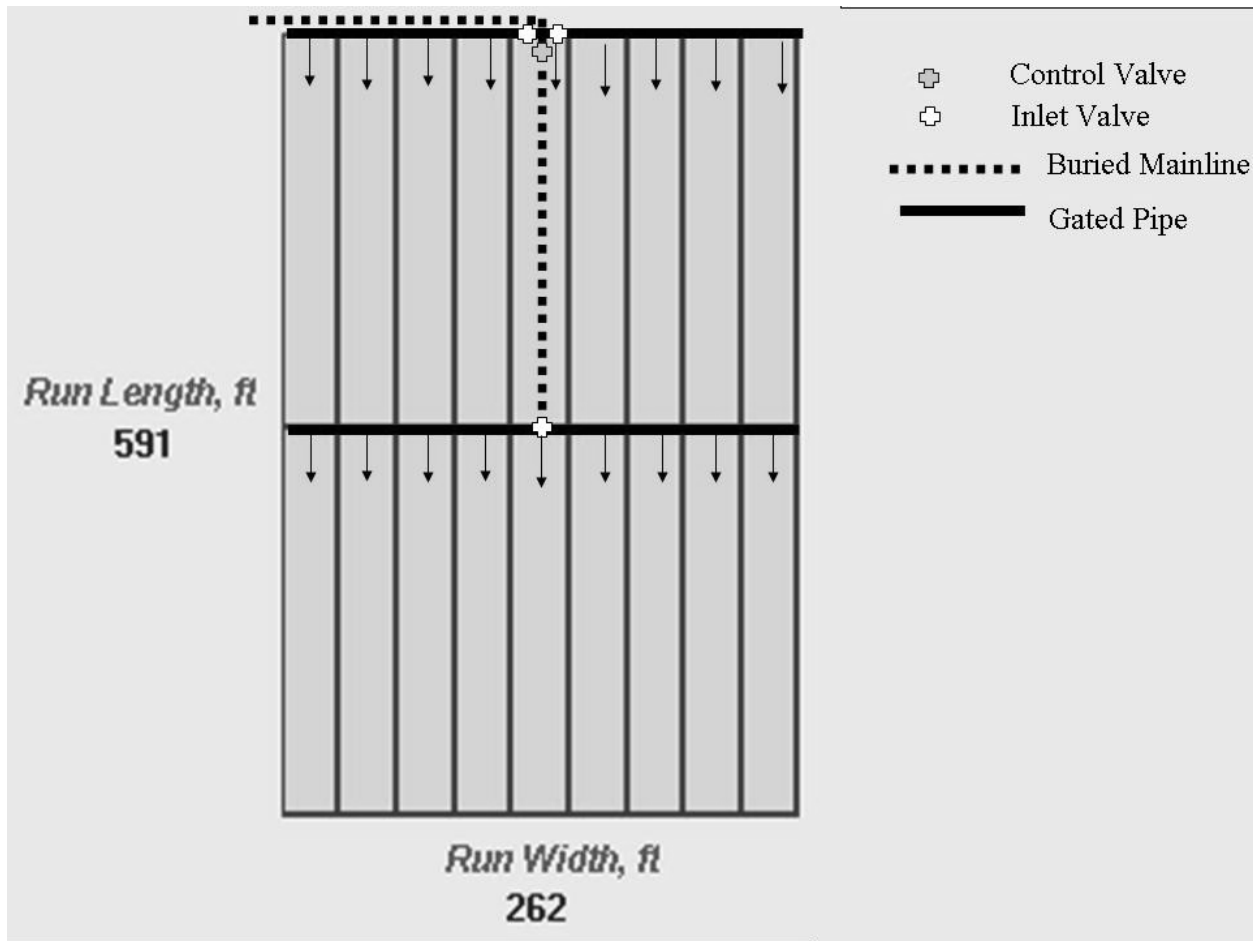
Figure IV-19. Layout of FreeDrainingFurrow_1 gated pipe system.

A conservative estimate of the friction loss in the supply pipe can be determined from Eq. IV.11 by using the canal free surface as the reference point. Thus:

$$h_f\big|_{supply\ pipe} = \frac{0 - (0 - 15\ feet) - 6}{1500/100} = 0.6\ ft/100\ ft$$

From Table IV-4, it can be seen that a 2,400 gpm flow with a 0.06 ft/100t friction gradient can be conveyed with a 16-inch pipe.

The pressure head at the 90° turn into the field is 6 feet. Three valves are situated at the upper to regulate flow to the left and right branches of the gated pipe as well as to control to the lower section. At the mid section of the field a two-way valve can be located to shift the flow into the right or left branches. The gated pipe sections extend in either direction for 1180 feet. From Fig. IV-18 a flow of 22.5 gpm will require a head of about 0.6 feet. Thus, the friction gradient computed from Eq. IV-11 for the pipes running uphill is:

$$h_f = \frac{6 - (0 + 0.0001 \times 1180) - 0.6}{1180/100} = 0.448 \; ft/100 \; ft$$

From Table IV-4, the gated pipe should be at least 16 inches in diameter. Generally pipe this big could only be supplied as lay-flat plastic tubing.
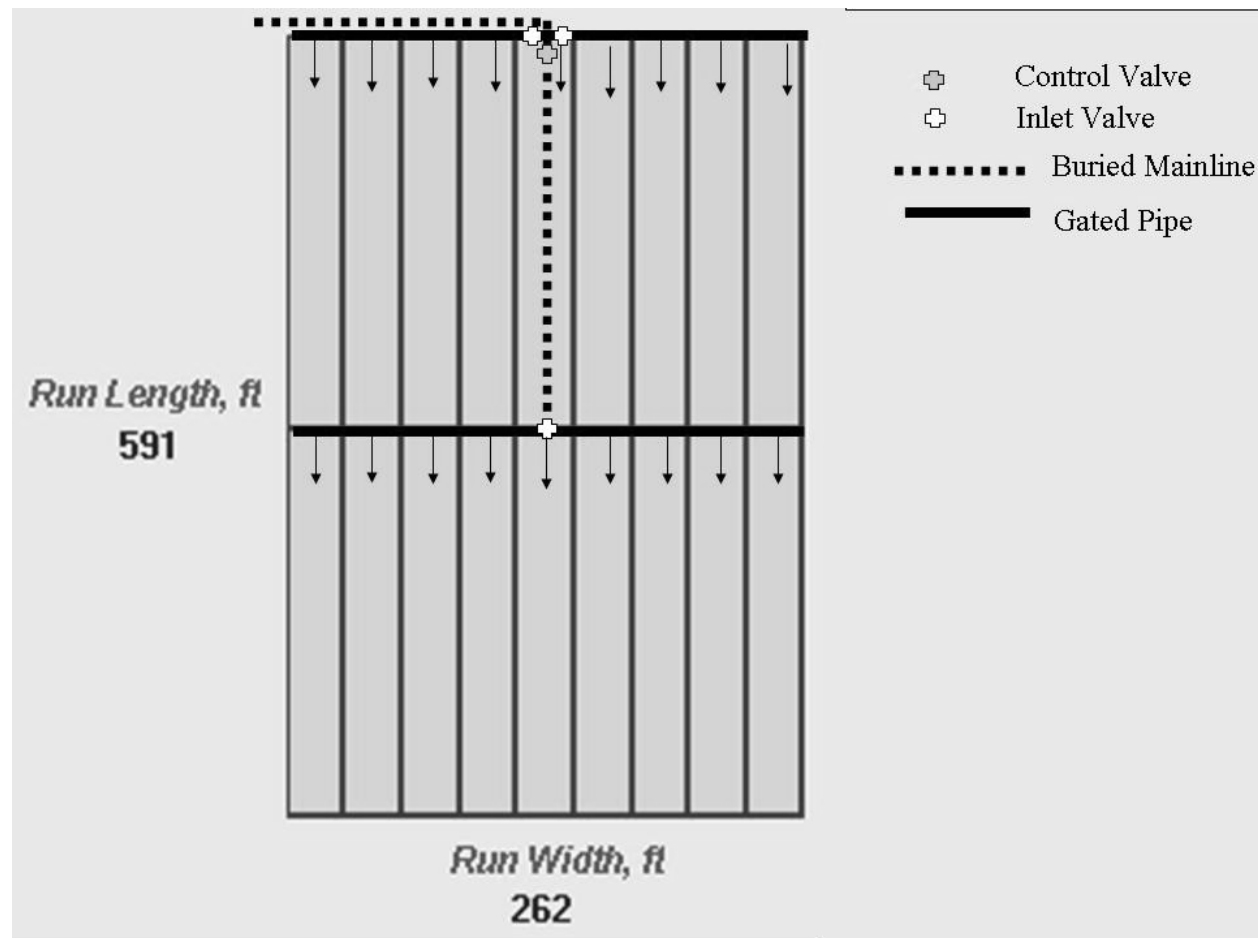
Figure IV-19. Layout of FreeDrainingFurrow_1 gated pipe system.

It may not be desirable to use large diameter lay-flat diameter gated pipe. In order to reduce the diameter and allow the irrigator a choice between aluminum, pvc, and lay-flat pipe, the main supply pipes need to be reconfigured.

Figure IV-20 shows an alternative design in which the gated pipe layout is subdivided in order to reduce the size of the pipe. In this case the supply pipes still carry the entire 2,400 gpm and are the same diameter as above. There are nearly 1,200 feet more of these pipes however. The individual gated pipes are now only 390 feet long. The friction gradient for this case is:
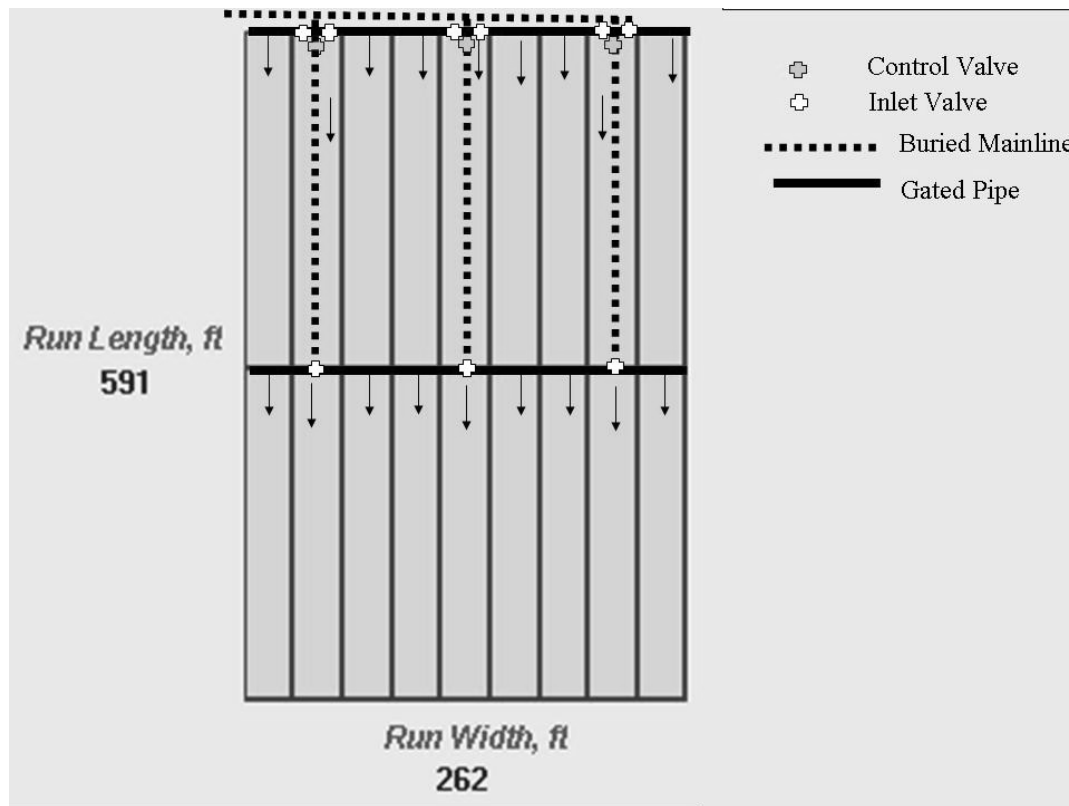
$$h_f = \frac{6 - (0 + 0.0001 \times 390) - 0.6}{390/100} = 1.375 \; ft/100 \; ft$$

From Table IV-4 this would probably require only a 12 inch pipe and therefore could be lay-flat, aluminum or polyvinyl. However the irrigator and designer might consider it unlikely that the savings in gated pipe cost would compensate for the additional buried mainline.

Figure IV-20. Alternative gated pipe layout for FreeDrainingFurrow_1.

IV.4.3 Comparing Alternatives for Headland Facilities

This section is not meant to be a comprehensive treatment of headland facility design, but to illustrate some basic principles and methodologies. Keeping in mind that most work to modernize or improve surface irrigation systems will occur within existing systems, a workable if perhaps suboptimal solution will present itself upon initial inspection. Specifically, one indication of what should be done to improve the function and efficiency of headland facilities is to improve what already exists.

There are no reliable criteria that would allow a designer to determine the best head ditch or pipe with their various offtake options without a site assessment. One only need visit an irrigated area to find many combinations of headland facilities doing essentially the same tasks

but doing so in a manner that suits the irrigator best. Historically, selecting irrigation facilities has been primarily concerned with the cost side of cost-effectiveness. However, with the goal of modernization in mind and anticipating that effectiveness will become increasingly important, irrigation efficiency will be substantially more important in the future.

Perhaps one of the most important features of surface irrigation systems of the future will be the capability to precisely regulate the unit flows onto the field. This requires that the total flow to the field be known accurately and that the unit flows can be achieved precisely. Earlier sections of this chapter have demonstrated that when the proper flow is added to a border, basin, or furrow, high uniformities and efficiencies will result. This suggests that adjustable gates are better selections than checks, spiles, or siphons. Seepage and leakage losses from the headland facilities should be minimized which suggests lined head ditches or pipelines.

One of the most important factors in choosing a particular type of headland facility, a head ditch or pipe for instance, is the type of surface irrigation system being serviced. As a rule, pipes that carry the flow necessary for border or basin irrigation are far more expensive than lined or unlined ditches. Outlets from head ditches for border and basin irrigation systems should have a high flow capacity and therefore the outlets are generally slide gates or checks. The smaller ditch gates, siphons, and even gated pipe should not be ruled out where the soils have low intake rates and/or the fields have relatively high slopes. Furrow irrigation systems on the other hand work best when flows to individual furrows can be regulated. This can be accomplished by siphon tubes, spiles or ditch gates from a head ditch or by gated pipe. Since the gated pipe outlets are more easily regulated than siphons, spiles, or ditch gates many irrigators engaged in improving their systems' performance choose gated pipe.

Another important factor is the flexibility to accommodate changes in cropping patterns. The crop rotations of some farming units involve border irrigation for some crops and furrow irrigation for others. A head ditch with ditch gates works well in both circumstances but gated pipe might be equally effective, particularly if intake rates are low.

Finally, labor is rapidly becoming the farm's most critical shortage and any surface irrigation system modernization and improvement program must reduce the labor required to operate it effectively if efficiency is to be increased. Automation is the ultimate labor saving technology. Thus, all things being equal, the best headland facilities might be those that can be automated.

However the headland facilities are selected, they must be capable of delivering the proper unit flow to the field under varying conditions through the season and year to year.

Appendix A. A Note on the Development of the Original NRCS Intake Families and Their Modifications for Furrow Irrigation

A.1   INTRODUCTION

In the 1950's various personnel of the Soil Conservation Service (SCS) of the USDA began a concerted effort to develop general intake relationships to support surface irrigation assessments when field measurements were not available. In the 1950's, 1670 ring infiltrometer tests were made in grass and alfalfa fields of Colorado, Wyoming, North Dakota, South Dakota, and Nebraska. Most but not all of the tests were conducted within irrigated fields. The individual tests were averaged in groups of five for analysis.

In 1959, J. T. Phelan proposed the intake families now found in the USDA-SCS National Engineering Handbook, Section 15, Chapters 4 – Border Irrigation and 5—Furrow Irrigation. As the need to revise the NEH to make it current with existing surface irrigation technology emerged in the late 1990's, so too did the need to re-examine and revise the intake families.

A.2   EVOLUTION OF THE ORIGINAL CONCEPT

The ring infiltrometer data collected in the 1950's were evaluated in several ways using principally regression. One of the first concepts explored was that of the "basic intake rate" which was defined as, "that rate when the change of the rate per hour was one-tenth of its value in inches per hour." In assuming initially that intake could be represented by the function,

$$z = k\tau^a + c \tag{A-1}$$

in which z is the cumulative intake in inches, τ is the intake opportunity time, in minutes, and k, a and c are empirical constants. The definition of basic intake rate, I_b, in inches per hour, was then,

$$I_b = \frac{\partial z}{\partial \tau} \ \bigg\| \ when \ \frac{\partial^2 z}{\partial \tau^2} = abs\left(0.10\frac{\partial z}{\partial \tau}\right) \tag{A-2}$$

This relationship occurs when,

$$\tau = -600\left(a - 1\right) \tag{A-3}$$

The basic intake rate thus defined was extracted from the ring infiltrometer data and grouped into 10 layers represented by averages of all the tests within the layer. The time to infiltrate 1, 2, 3, 4, and 6 inches were interpolated from each of the 5-reading averages and then averaged over the layer as shown in Table A-1. Then the Philip equation was used to fit the data in Table A-1. The expression of the Philip equation is

$$z = S\tau^{0.5} + A\tau \tag{A-4}$$

in which S is the soil "sorptivity" and A is the soil "transmissivity",[12] and the resulting fit with the layer ring data produced the following relations:

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[12] Philip, J. R. 1957. The Theory of Infiltration: 4. Sorptivity and the Initial Moisture Content and 5. The Influence of the Initial Moisture Content. Soil Science 84:257-337.

TABLE A-1. LAYERED SCS RING INFILTROMETER DATA.

Range of I_b, in/hr	No. of Test Groups	Average					
		I_b, in/hr	τ_1, min	τ_2, min	τ_3, min	τ_4, min	τ_6, min
Under 0.1	7	0.084	262	1146	2913	5770	15600
0.11-0.20	21	0.141	136	545	1288	2407	6002
0.21-0.40	35	0.291	65.1	209	439	731	1510
0.41-0.70	49	0.542	40.5	119	223	344	626
0.71-1.25	80	1.02	22.0	64.8	118	176	313
1.26-1.80	54	1.49	12.9	39.5	75.1	119	239
1.81-2.40	23	2.16	11.4	32.1	53.9	78.5	132
2.41-3.40	29	2.89	7.85	22.5	40.2	59.6	101
3.41-4.80	18	3.93	6.38	17.5	30.6	42.6	73.2
Over 4.80	18	5.71	4.27	11.1	21.2	30.7	51.3
Total	334						

$$S = 0.1766 \cdot I_b^{0.392} \tag{A-5}$$

and

$$A = 0.01282 \times I_b - 0.00175, \quad B \geq 0 \tag{A-6}$$

Values of S and A were then computed for I_b values corresponding to the SCS (now NRCS) Intake Family designation, 0.05 in/hr to 4 in/hr. Rather than use these values as the basis for the intake families, it was decided to convert Eq. A-4 to the form of Eq. III-19:

$$z = k\tau^a + c \tag{A-7}$$

This was accomplished by using Eqs. A-4—A-6 to compute values of τ for three values of z, 1, 3, and 9 inches. Then values of k, a, and c were computed from the three points and became the NRCS Intake Family values in use until the publication of this chapter.

A.3   MODIFICATIONS FOR FURROW IRRIGATION

Throughout the 1950's and 1960's a small group of SCS personnel also wrestled with the question of how to represent infiltration in furrow irrigation. Field data were sparse but there were data which suggested that intake could be related to flow, slope, and roughness – in other words wetted perimeter. There was also some understanding that infiltration from the furrow sides was occurring at different rates than from the furrow bottom.

The methodology for developing intake relationships from advance, recession, and inflow-outflow was not well understood. Nevertheless, SCS personnel were making field

measurements and attempting to determine intake parameters. By the late 1960's, these analyses generally centered on adjusting the original intake family coefficients for wetted perimeter. Specifically, furrow irrigation intake was expressed as:

$$z = \left(k\tau^a + c\right)\left(\frac{wp}{w}\right)$$

(A-8)

in which *wp* is the furrow wetted perimeter in feet and *w* is the irrigated furrow spacing in feet. The *wp/w* adjustment was limited to a value no greater than 1.0.

A substantial effort was made to express wetted perimeter as a function of flow, Manning *n*, furrow slope, and furrow shape. Values of Manning *n* were typically 0.03 or 0.04 and the furrow shape was generally represented as trapezoidal. The concept of a furrow-based "basic intake rate" was maintained. In the end, the concept of relating basic intake rates in cylinder and furrow tests was abandoned. Instead, a fairly large number of values of wetted perimeter were computed using trapezoidal shapes ranging from a 0.2 ft bottom width and 1:1 side slopes to 0.5 ft bottom widths with 2:1 side slopes. Values of flow, slope, and Manning *n* were included in the analysis. The data were then simulated by the following relation:

$$wp = 0.2686\left(\frac{Qn}{\sqrt{S}}\right)^{0.4247} + 0.0462$$

(A-9)

where *wp* is the wetted perimeter in feet, *Q* is the flow in gpm, *S* is the furrow slope, and *n* is the Manning *n*.

The differences between lateral and vertical infiltration were introduced by adjusting the 0.0462 constant in Eq. A-9 by 0.7 to a new value of 0.7462. The basis of this adjustment is described in Chapter 5 (Second Edition), "Furrow Irrigation", Section 15 – Irrigation, or the National Engineering Handbook, page 5-30 as:

> "To account for both vertical intake, which is influenced by gravitational forces, and horizontal intake, which is influenced by suction forces, the wetted perimeter is increased by an empirical constant of 0.700. This factor is an average value derived from studies that indicate that horizontal intake is a function of the 0.4 power of intake opportunity time."

A.4   MODIFICATIONS FOR BORDER, BASIN, AND FURROW IRRIGATION

A.4.1   NRCS Intake Family Designation

The basic infiltration rate generally occurs substantially beyond the time when, "that rate when the change of the rate per hour was one-tenth of its value in inches per hour." A more rationale and understandable concept for an intake family would be the average 6-hour intake rate. A plot of the 6-hour intake rate for each of the previous NRCS intake curves is shown in Figure A-1. Given the ambiguity of the definition of basic intake and the problems associated with this definition in the Kostiakov intake equations, it seems reasonable to modify the concept of the intake family to one based on the average 6-hour intake rate in inches/hour. Furthermore, the ring data originally used to develop the intake families have two very serious limitations. First, they do not deal with the initial irrigations following cultivation. And second, they do not

represent the physical condition where water flows over the surface and displaces soil. Thus, a change in how the families are defined can be made without serious physical limitations.
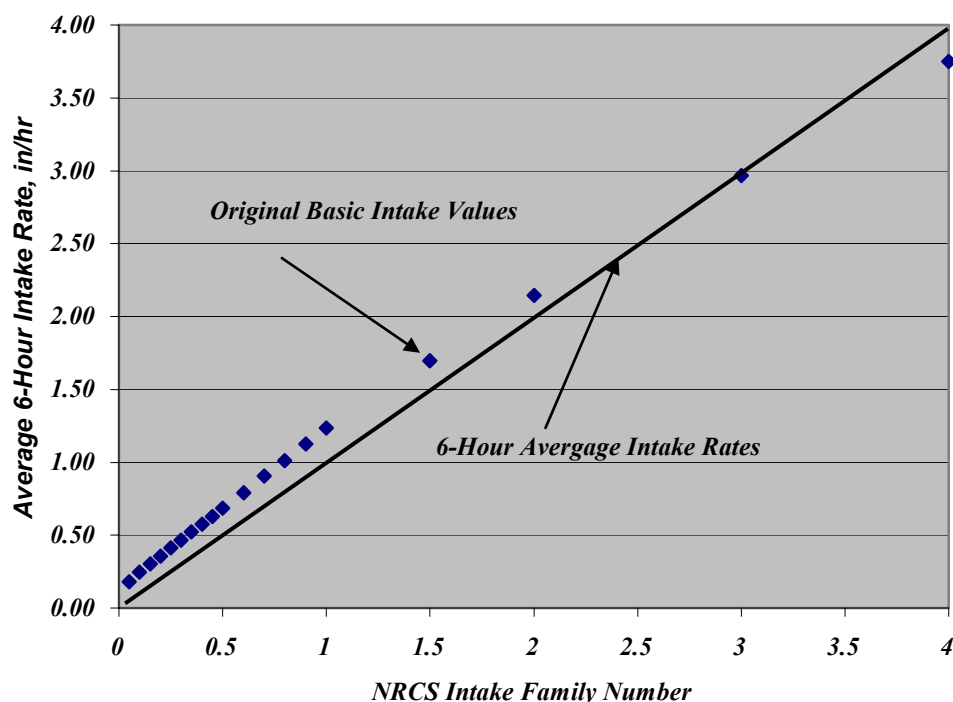
Figure A-1. Comparison between the average 6-hour intake rate and the basic intake rate of the original SCS intake families.

A.4.2 Adjusting Intake for Furrow Irrigated Conditions

Furrow intake is independent of furrow spacing until the wetting patterns between furrows begin to interact or overlap. When the original SCS manuals were written with the furrow adjustments based on the ring infiltrometer equations there were few actual furrow intake measurements and measurement methods in place. Thus, it was necessary and rational to accommodate furrow irrigation by adjusting one-dimensional ring functions in the late 1960's. It is no longer rational because more data are available and more sophisticated analyses have been developed.

In addition, there are now two fundamental pieces of data associated with furrow intake measurements that render Eqs. A-8 and A-9 obsolete. First, the flow of each furrow measurement, as well as the actual wetted perimeter, is known. It is no longer necessary to approximate neither Manning *n* nor the furrow shape. Consequently, the reference state for any furrow intake measurement is the flow and wetted perimeter in the furrow at the time of the measurement. Any adjustment for different flows or different shapes and wetted perimeters on the same soil should be made on the basis of an adjusted wetted perimeter and not the furrow spacing. The revised intake families of Section III are based on this modification.

A.4.3 Converting Between Border/Basin Infiltration and Furrow Intake

At the time of this manual preparation, the number of furrow intake measurements available for evaluation in the general sense is substantially greater than measurements

corresponding to border/basin irrigation. Consequently, it is suggested that the historical practice found in earlier NRCS documents in which the furrow intake is derived from border/basin infiltration should be reversed. Furthermore, it is no longer realistic to ignore the intake characteristics of the initial irrigations. In this manual, the reference intake family has been based on the estimated 6-hour intake rates of freshly formed furrows with a corresponding reference flow and wetted perimeter. Estimates of border/basin infiltration curves are then derived by multiplying the furrow K and F_o and parameters by the ratio of furrow wetted perimeter to the unit width to determine their border/basic counterparts, k and f_o:

$$k = \frac{K}{WP_r}, \ f_o = \frac{F_o}{WP_r} \tag{A-10}$$

in which WP_r is the reference wetted perimeter at which the furrow families are defined.